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The State of an Emerging Technology and a Look at What Lies Ahead
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Robotics: Mobility, Reflexes and Teamwork

Executive Summary

Today's commercial robots are either multi-million dollar planet explorers or simple mechanical pets and vacuum cleaners.

Research lab prototypes are more interesting, ranging from autonomous cars to the latest attempts at humanoids to artificial insects.

The keys to making robots much more useful than today's commercial models are mobility and autonomy. These traits encompass many scientific and engineering challenges: practical dynamic balancing schemes for robots with legs, ways to manipulate objects without hurting them, more efficient power sources and power use, better sensors and ways to interpret sensor data, better navigation strategies, and coordination with other robots and with humans.

Robotics research is closely linked to artificial intelligence research. Most robot intelligence research is focused on enabling or improving behaviors like navigation and obstacle avoidance. The near-term goal is to allow people to send robots high-level commands without having to worry about lower-level behaviors like obstacle avoidance.

Robots with this ability have the potential to be our eyes, ears and hands in places that are too remote, dangerous or small for humans.

Researchers are also beginning to use artificial intelligence techniques to allow robots to carry out useful tasks. More sophisticated interaction abilities will enable teams of robots that can be directed by humans, and eventually robotic waiters, salespeople and entertainers.

Small robots that perform simple household tasks could become practical in five to ten years, autonomous robots are a decade away, and broadly useful humanoid robots will take several decades to emerge.

The ultimate in automation is a machine that reproduces and evolves. This area is highly speculative, but researchers are beginning to combine evolutionary design and automated production. Nanoscale machines are also highly speculative; these are decades away and unlikely to be as sophisticated as their larger equivalents.

What to Look For

Mobility:

Lightweight, long-lasting power supplies
Practical snake-like robots
Practical insect-like robots
Humanoid robots with human-like movement

Perception:

Sensor-fusion-based perception
Lightweight, low-power vision systems
Optical "nervous system" interconnects

Decision-making/Autonomy:

Robotic vehicles on public roads
Robot-controlled drug design
Robot-controlled genetics research

Human-robot interaction:

Layperson mobile robot control interfaces
Robots that learn through social interaction
Mixed human-robot teams
General-purpose household robots
Conversationally interactive humanoid robots

Microrobots:

Microrobots powered by artificial muscles
Autonomous flying microrobots
Microrobotic surgical tools

Self-Constructing/Self-Configuring:

Practical modular robots
Evolutionary adaptation of robotic subsystems
Automated design and manufacturing of machines

Machines like us

Tasks that seem easy for a human — catching a ball, recognizing an object, walking, learning the rules of a game, coming up with a solution to a problem, answering a question — only seen easy because these skills have been honed over the ages.

In aiming to imbue mobile autonomous robots with these abilities researchers have set a daunting challenge: finding a way to mimic the results of hundreds of millions of years of evolution.

The unrealistic expectations set by science fiction and early artificial intelligence research have implied that by now we all should have robotic maids a la The Jetsons. In reality, today's robots are either multi-million dollar planet explorers or simple mechanical pets and glorified vacuum cleaners.

Things are a little more interesting in research labs, however, where prototype robots range from autonomous cars to the latest attempts at humanoids to artificial insects that are perhaps a few years away from serving as scouts, spies and surveyors.

For all of these potential capabilities, though, the most basic behaviors of remaining upright and avoiding obstacles are major accomplishments. This became abundantly clear on March 13, 2004 during the Grand Challenge, a Defense-Department-sponsored 142-mile road race for robotic vehicles. None of the thirteen competitors made it 8 miles, nine failed before the one-and-a-half mile mark, and three didn't make it out of the starting area.

This report provides an overview of the state of robotics research, examines the many approaches researchers are taking, and looks at the prospects for useful robots.

Autonomy and utility

Robots have for decades performed industrial tasks that would be exceedingly tedious for humans.

In this capacity they are precise and fast. These robots are also fixed in place and their programming is limited to specific, assembly-line tasks.

The key to making robots much more useful is making them more mobile and autonomous. Robots have the potential to be our eyes, ears and hands in places that are too remote, dangerous or small for humans. Eventually they could become full-fledged surrogates in these environments.

The goal is to make machines that can perform a wide range of tasks, receive varied instructions, adapt to changing circumstances, learn as they go and above all don't need to be told what to do every step of the way. This is the ongoing focus of robotics research, and it encompasses a host of challenging scientific and engineering problems.

Robotics research falls into eight categories:

- mobility: giving robots the ability to move through the environment
- manipulation: giving robots the ability to move, lift and restrain objects
- power: giving robots long-lasting, easily replenished energy sources
- perception: giving robots the ability to receive and interpret sensory data
- navigation: giving robots the ability to move to particular locations

How It Works

Navigation

Navigation is nothing more than plotting and efficient route from point A to point B. Fundamentally, robot navigation includes just two things: the ability to move and a means to determine whether or not the goal has been reached.

The trick is finding the most efficient way to reach a destination. There are several aspects to this seemingly simple problem and several ways to solve it.

In the age of sailing, navigating meant finding the ship's position using the stars, charting the position on a map, drawing a line from present position to destination, and deriving the compass heading for the ship to follow. Today's ship navigation uses Global Positioning System readings rather than the stars and electronic maps rather than paper ones, but the principle is the same.

This doesn't work in all situations, however. An autonomous mobile robot might not have a map of its environment handy or be able to determine its position, but it still requires a means to get where it's going.

In instances like these robots need to be able to navigate more like people, who can read maps ("you are here"), follow a heading ("go four blocks north"), recognize landmarks ("turn left at the store with the big purple sign") and use waypoints ("the meeting is at 125 Main St., 4th floor, room 10").

There are major three types of robot navigation.

Big picture

A robot that uses map navigation must have a global representation of the environment. The robot makes some kind of measurement to find its position, and plots a course to its destination. The robot has knowledge of all the locations in the environment and how they are related to each other, and knowledge of its own relationship to the locations. If the robot is initially given its position on the map, it doesn't need any information about its surroundings to reach a destination.

Bread crumbs

A robot that uses waypoint navigation follows a sequence of recognizable landmarks to reach a destination. The robot is aware of locations beyond its sensor range, but does not know the relationships among the locations. It finds its way from one landmark to the next using local navigation techniques. Robots can also use waypoint navigation to build maps for subsequent map navigation. When multiple sets of waypoints can be used, the robot must be able to plan a route.

- decision-making: giving robots the ability to select from alternative courses of action
- coordination: giving robots the ability to work in teams
- human-robot interaction: giving robots the ability to communicate with people

Researchers are tackling these issues, trying to keep costs reasonable, and looking to find uses for robots beyond interplanetary exploration and military applications.

Getting around — walking, hopping, slithering and flying

Mobility is a challenging problem. Industrial-age machines and nature both provide many examples that can be applied to robot locomotion, but these have been designed or have evolved for specific environments or tasks. Automobiles, for example, are fast and can carry heavy loads but require roads, and birds can fly but need open spaces.

One major question in robot locomotion is whether to use wheels or legs, and how many. Wheels are simple and stable but are usually stymied by stairs and mud. Six-legged, insect-like locomotion is also stable, but relatively slow and the broad footprint required makes it appropriate only for smaller robots.

Although the flexibility of bipedal locomotion is tempting, especially for robots that operate in human environments, it is a difficult engineering problem. Walking, running, jogging, tiptoeing, and skipping may all seem easy, but they are all complicated motions that involve precise control.

Opening doors

Making a humanoid robot means solving a difficult balancing problem. Upright structures on two legs are inherently unstable. Even in nature, bipedal locomotion, found principally in primates and birds, is often clumsy and usually slow.

In engineering terms, upright robots require dynamic balancing, meaning their attitude sensors must coordinate with their mechanics so that they balance like an inverted pendulum. When a pendulum is moved, gravity returns it to a state of equilibrium. Dynamic balancing plays the role of upside down gravity for an inverted pendulum.

A dozen projects at universities and government labs around the country involve building robots on bases made from the bottom half of a Segway scooter, which uses gyroscopes to provide dynamic balancing. The projects were initiated by DARPA as part of its Mobile Autonomous Robot Software (MARS) program.

Researchers from the Massachusetts Institute of Technology used a robotic arm and a Segway scooter to construct a robot that can traverse hallways and open doors. The robot, which will eventually have three arms, is designed to be able to interact with humans safely and at eye level. (See “Segway Robot Opens Doors”, page 10)

How it looks from here

A robot that uses local navigation taps sensor data to determine its position relative to observable landmarks and compares this to the destination’s position relative to the same landmarks. The robot changes its position until it matches the destination. Local navigation requires robots to be able to recognize destinations, aim for them, and hold a course.

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Though dynamic balancing is an engineering challenge, the physics of walking shows that bipedal locomotion doesn't even require an active power source.

Researchers from Cornell University have figured out the mathematics behind the mechanics of human motion by explaining the movement of a Tinkertoy that walks like we do. The toy, a passive dynamic walker, is powered and directed only by gravity and moves in all three dimensions but cannot stand up unless it is moving. (See "Toy Shows Bare Bones of Walking", page 12.)

Researchers have been working to make bipedal robots for many years, and in the last few years simple humanoid robots have become commercially available, including Sony's Qrio, Honda's Asimo and Fujitsu's HOAP1 and HOAP2. Over the next 10 years, larger, more stable and more mobile humanoid robots are likely to emerge.

In the meantime, wheeled human-scale robots will provide comparable mobility on level surfaces.

Snakes, frogs and bugs

Widescale use of humanoid robots is likely to be decades away. But other forms of non-wheeled mobile robots are likely to arrive sooner. Various animals are inspiring productive prototypes. Several research teams are working on making relatively small robots that crawl insect-style. Others are taking inspiration from amphibians and reptiles.

Researchers from NASA's Jet Propulsion Laboratory and the California Institute of Technology have developed a robot that can both roll and hop. The researchers' one-kilogram frogbot has wheels and a spring-loaded leg that allows for hops as high as 1.8 meters in Earth's gravity, which translates to six meters on Mars. (See "Exploratory Robot Hops and Rolls", page 13.)

NASA and Palo Alto Research Center (PARC) researchers have designed a multi-segment snake robot that has contact-sensing ribs that allow the robot to gauge terrain as it moves. The idea is to give the robot the ability to automatically figure out what kind of surface it's on and switch to the means of movement most appropriate for that surface. In addition to various snake-like motions, the Snakebot can stand upright to gain a better view, and can fix itself to surface at one end and manipulate objects with its other end. Snake-like motion has the advantage of being fairly fault-tolerant. If one segment fails motion is still possible. (See "NASA Gets Snake Robot off the Ground", page 15.)

Researchers from the University of Cambridge in England and Lehigh University have shown that it is possible to make a strip of hybrid gel mimic the movements of the snail, inchworm and snake. The ability could lead to new motion techniques for small robots. (See "Gel Gains Life-like Motion", page 15.)

Buzzing around

Flying is an especially appropriate form of locomotion for small robots. Several research groups working on flying robots are teasing out secrets from the experts — insects.

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Two major flying insect robot efforts are underway: the micromechanical flying insect (MFI) project at the University of California at Berkeley and the Entomopter project at the Georgia Institute of Technology, University of Cambridge in England and ETS Labs.

Researchers from the University of Cambridge in England have tapped tethered hawkmoths and flapping robots to show that wing movement creates columns of spinning air, or forces above the leading edges of wings, which provides the lift needed to fly.

Researchers from University of California at Berkeley have used robotic fruit fly wings to discover that fruit flies capture turbulence from their own wakes to increase lift.

Researchers from Oxford University in England have trained red admiral butterflies to fly between artificial flowers in a wind tunnel and have recorded the way air flowed around their wings using smoke and high-resolution cameras. These free-flight studies prove that butterfly flight is much more complicated than previously thought. The researchers found that butterflies used all of the known mechanisms to enhance lift — wake capture, leading-edge vortex, clap and fling, and active and inactive upstrokes — and they discovered a couple of new ones — leading-edge vortex during the upstrokes, and double leading-edge vortex. The same strategies could be used by robotic flyers that weigh between 100 milligrams and 10 grams. (See “Butterflies Offer Lessons for Robots”, page 16.)

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Getting a grip

Picking up, taking apart, adjusting, and throwing are all second nature to humans. It turns out that manipulating objects is another challenging problem for robotics researchers, however. Giving a robot even the simple ability to move an object involves finding the right type of grip, the right amount of force, and the most useful type of sensor feedback.

Researchers from Pennsylvania State University have unearthed the mathematical secret used instinctively by a person bouncing a ball on a racket and taught the trick to a robot arm. To control a bouncing ball, a racket’s upward motion must be slowed down slightly just before it hits the ball. The researchers are ultimately looking to identify the many underlying mechanisms that allow humans to naturally find and use basic movement principles. (See “Robots Learn Soft Touch”, page 18.)

NASA researchers have put together a robotic hand that closely mimics the inner workings of the human variety. The robotic right hand, wrist and forearm boasts 12 degrees of motion and contains 42 sensors that track the position and velocity of the hand’s moving parts. (See “NASA Grasps Intricacies of Human Hand”, page 19.)

Robotic arms are the most common type of manipulator, but manipulation needn’t follow biology’s lead.

Researchers from the University of California at Berkeley have devised a way to use vibration to move objects around a flat surface. Their Universal Part Manipulator consists of a computer, camera and a surface outfitted with flexible legs and four motors. The device is capable sorting poker chips by color. (See “Shaky Tabletop Sorts Parts”, page 20.)

Source of strength

Power consumption is a major issue. Robots typically have a drive mechanism, an array of sensors, computer processors, manipulators and communications devices, which all draw power and contribute to the robot’s weight. Robots have to carry their power source with them, most often batteries, which are relatively heavy and require frequent recharging. A common capability of robots that operate indoors is finding electrical outlets and plugging into them when their batteries run low.

An important aspect of both manipulation and mobility is the robotic equivalent of muscle power. Common electric motors can drive wheels and arms, but materials that mimic muscles are often more appropriate for smaller and lifelike robots.

Researchers at Pennsylvania State University are working on artificial muscle materials designed to be used in actuators for motors that work much like biological muscles. The material changes shape in the presence of electricity, eliminating the need for moving parts, and can be used in very small robots. (See “Small Jolts Move Artificial Muscle”, page 21.)

Artificial muscles could be used in robotics in five to ten years.

Do you see how I see?

Perception is arguably the biggest challenge in robotics research. Cameras, microphones and force sensors do a reasonable job of approximating eyes, ears and nerve endings, and the sensory input is a relatively straightforward engineering problem. The difficulty of producing artificial sight, hearing and touch lies in giving robots the means of interpreting sensory data in useful ways.

Artificial vision, for example, requires pattern recognition algorithms that extract depth perception and object recognition from a jumble of color and brightness data. Processing sensory data in real time takes a lot of computer power.

Researchers from the State University of New York in Buffalo and Stanford University have turned to nature to tackle the problem. They have built a silicon retina that uses a timing signal to mimic a form of data compression performed by biological eyes. The electronic retina processes the data that makes up an image, culls the edge information needed for detecting and tracking objects, and transmits the information as high-speed optical output. (See “Vision Chip Shines”, page 23.)

Researchers from the California Institute of Technology have built a vision chip whose design is based on the eyes of jumping spiders. Jumping spiders’ vision rivals that of humans, but their eyes contain many fewer photoreceptors. The researchers’ design mimics the jumping spider’s trick of rotating its retinas to glean more information from the environment using fewer photoreceptors. The researchers have designed eyes suitable for mid-size robots and for small, flying robots. (See “Shaky Chip Makes for Bug-Eyed Bots”, page 26.)

Researchers from the University of Kentucky have found a simple, relatively low-cost method to measure depth using a single camera. The method involves shining a light pattern onto an object and gaining depth information from the way the object distorts the pattern. The scheme could lower the costs of basic computer vision systems that enable computers to locate people and sense gestures. (See “Light Show Makes 3D Camera”, page 24.)

A growing area of research in the field of robot perception is sensor fusion, or the correlation of several types of sensor input to derive a more accurate understanding of the environment. Work in this area has focused on combining vision, sonar and laser range-finding data for robotic rovers.

Finding the way

Once a robot can move and perceive its environment, it needs to know how to get from point A to point B without running into anything along the way. This involves planning routes, avoiding obstacles and adapting to changes in the environment like moving obstacles and blocked paths. Robot navigation is central to several tasks commonly assigned to robots: exploration, foraging and search-and-rescue missions.

There are three types of robot navigation: those that follow maps of the environment, either existing or created on-the-fly from sensor data; those that use a set of recognized locations or landmarks as waypoints; and those that compare sensor data to data representing a target location and change position until they match. (See How It Works, page 2.)

Most robot navigation systems use vision or sonar. Researchers from the University of Toronto have taken a different tack — sound. Their lab tour robot finds its way around using a system of 24 microphones and embedded around the lab. The system requires about two seconds of sound to get enough information to peg the robot’s location within seven centimeters. (See “Robot Guided by Its Voice”, page 27.)

Making decisions

Robotics research is closely linked to artificial intelligence research. General-purpose autonomous mobile robots clearly need a high level of machine intelligence, and recently researchers have began to recognize the value of embodiment in developing artificial intelligence.

Most robot intelligence research is focused on enabling or improving behaviors like navigation and obstacle avoidance. Researchers are also beginning to use artificial intelligence techniques to allow robots to carry out useful tasks.

Researchers from the University of Wales, Robert Gordon University in Scotland, and the University of Manchester in England have put together a robot scientist that you might miss if you looked around the room for it. It consists of a computer running artificial intelligence software, a fluid-handling robotic arm, and a plate reader that checks the experimental results for variables like color.

Its actions, however, are eerily human-like. The robot scientist can devise a theory, come up with experiments that test the theory, carry out the experiments, and interpret results. The robot scientist gets its smarts from a branch of artificial intelligence dubbed active learning, which involves algorithms that consider the odds of hypotheses being correct and the costs of potential experiments to determine the optimal series of experiments to eliminate all but the correct hypotheses. (See “Robot Automates Science”, page 28.)

All together now

Another growing area of robot research involves coordinating teams of robots, particularly for military and space applications. The area overlaps the field of multiagent systems research, which also includes software-only systems like Internet-based intelligent agents. Robot coordination requires robots to be able to communicate with each other, track each other’s positions and divide tasks.

NASA researchers have demonstrated a pair of networked rovers that together can move large objects, drill holes and pitch tents. The 20-pound, four-wheeled, one-armed robots cooperatively map terrain, and react in real time to their physical positions and the weights of their payloads. (See “Cooperative Robots Share the Load”, page 31.)

Researchers from Carnegie Mellon University have put together a team of human-sized, soccer-playing robots that get their balance from the bottom half of a Segway scooter. The idea is to have mixed teams of robots and humans play soccer in order to explore questions like how and when robots and humans should communicate, and how they should divide a common task. The robots are designed to allow human-robot interactions that put humans and robots on a nearly equal footing. The two types of players have the same acceleration, top speed and turning abilities. (See “Bots, Humans Play Together”, page 32.)

Robots that coordinate their actions could be used practically in five to ten years.

Is it a he or a she?

One of the main goals of robotics will be realized when robots regularly interact with people in a variety of workplaces. The ability to interact well with humans will enable teams of robots to be directed by humans in industrial settings, and will pave the way for service and entertainment robots like embodied personal digital assistants, and robotic waiters and salespeople.

Good human-robot interaction requires robots that react appropriately to human behavior and communicate with people. The emerging field of robotic social intelligence, which encompasses technologies like dialog management and emotion recognition, is beginning to address the considerable challenge of producing robots that seem to understand us.

Fortunately, the relationship gets a considerable helping hand from the human tendency to anthropomorphize. Humans readily bestow a degree of social intelligence on machines, even those that don’t have even remotely human appearances.

Researchers at Carnegie Mellon University have created a robot personality in Horatio “Doc” Beardsley, endowing him with the ability to see, understand spoken words and carry on a conversation.

Doc Beardsley’s conversational abilities are the result of several layers of software and a couple of tricks. Synthetic interview software includes speech recognition abilities and a set of lines to deliver on anticipated topics. Where the interview software leaves off, a discussion engine picks up the slack, tracking questions and answers to glean keywords that the character can rely on. If that doesn’t work, Doc can toss the question back to the interviewer. And Doc’s cover as an absent-minded professor makes people more forgiving when, as a last resort, he simply changes the subject. (See “Interactive Robot Has Character”, page 33.)

Sophisticated human-robot interaction is a decade or more away. For now, human-robot interaction is largely a matter of people sending commands to robots. Research in this area aims to allow people to give robots high-level commands like going to a given location or carrying out a task without having to worry about of lower-level behaviors like obstacle avoidance.

Researchers from Carnegie Mellon University and the Swiss Federal Institute of Technology at Lausanne have developed software that allows for remote control of a robot over the Internet via a handheld computer controller. The robot, which contains five types of sensors — a video camera, stereo vision sensor, ultrasonic sonar, and in odometer — allows a user to explore a remote environment. (See “Software Eases Remote Robot Control”, page 36.)

Lilliputians

Robotics is also pushing down to ever-smaller size scales. Tiny robots have the potential to travel hard-to- reach places like narrow pipes, and microscopic robots could potentially traverse the human body.

Researchers at Sandia National Laboratories have built robots that weigh less than an ounce and move through terrain like carpet on tank-like treads at speeds as fast as 10 inches per minute. (See “Tiny Treads Move Miniature Robots”, page 37.)

Researchers from the University of Linköpings in Sweden have produced tiny robot arms that work in salt water. The arms measure about two-thirds of a millimeter across, and are capable of the picking up and moving a glass bead that is 100 microns in diameter, which is about the size of a human egg cell. (See “Tiny Robots Flex Their Muscles”, page 38.)

Microrobots could find practical applications in about five years.

Advances in nanotechnology and the attendant excitement about its potential have led to much speculation about nanoscale robots. Although nanoscale machines that can move and manipulate objects have been theorized, they are decades away and are unlikely to match the sophistication of their larger equivalents.

The shape of things to come

As machines, robots have several capabilities that are not possible the biological world: modularity and blazingly fast evolutionary development.

University of Southern California researchers have designed modular robots that move like snakes and spiders, have the ability to rearrange themselves, and communicate via an infrared communications scheme that mimics a biological hormone system. The self-assembling robots are made up of identical, box-like modules, and robots can exchange modules to make themselves bigger or construct a larger group of smaller robots. Each module includes a computer processor, batteries, a communications system and a pair of motors. Once two or more modules connect to form a structure, and several types of locomotion are possible. (See “Self-Configuring Robots Mimics Lifeforms”, page 39.)

Genetic algorithms mimic evolution by using copies of a piece of code to represent individuals, introducing random changes to the population, allowing the best results to continue to the next generation, mixing their traits, and repeating the cycle many times. The software can cycle through the process quickly enough to hone robot control software over the equivalent of thousands of generations in a matter of hours.

Researchers from North Carolina State University and the University of Utah have combined artificial neural networks and teams of real mobile robots to demonstrate that the behavior necessary to play Capture the Flag can be evolved in a computer simulation. They loaded the out-of-body experience into real robots, which were then able to play the game competently. (See “Evolution Trains Robot Teams”, page 41.)

The ultimate in automation is a machine that reproduces and evolves, which would remove even the burden of designing and building machines that meet humans’ needs. This area is highly speculative, but researchers are beginning to combine evolutionary design and automated production.

Researchers at Brandeis University have developed a system that allows populations of virtual robots to evolve toward a desired set of characteristics, then builds the robot body parts automatically using a rapid prototyping machine. (See “Robots Emerge from Simulation”, page 42.)

Practical modular robots are possible within a decade, but robots with evolutionary adaptive behavior or that design and build themselves are several decades away.

Coming home

Robots have existed in human imagination for centuries. From the crude beginnings in the early days of the integrated circuit to the present, one of the most reliable products of robotics research has been a growing understanding of just how difficult the task is.

Many research efforts involve Mars rovers and military robots, which are not truly autonomous but which have many of the basic capabilities that autonomous robots will need. The robotic rovers Spirit and Opportunity have been able to traverse the surface of Mars and carry out scientific experiments controlled by nothing more than high-level instructions like “go to point X”. Robot vision technology should mature considerably in the next five to ten years in conjunction with these research efforts.

At the same time, the field is poised to reach a milestone. Autonomous mobile robots are beginning to enter the home and workplace. Robots are making deliveries in hospitals, greeting customers in retail stores and entertaining people in their homes.

Increased interaction between people and autonomous robots will spur further applications and provide researchers with fodder for advancing the technology.

Small, human-shaped robots that perform simple tasks around the house could become practical in five to ten years, but broadly useful humanoid robots are still decades away. Practical non-humanoid autonomous robots, however, could emerge within a decade. Future Grand Challenge-like competitions should provide a good gauge of how quickly researchers are solving the many challenges involved in making machines move and act more like living things.

Recent Key Developments

Advances in mobility:

- A robot that can navigate a hallway and open a door. (Segway Robot Opens Doors, page 10)
- A robotic snail that moves across a film of silicone oil, Massachusetts Institute of Technology, September 2003
- An explanation of the physics of a passive dynamic Tinkertoy that walks the way humans do. (Toy Shows Bare Bones of Walking, page 12)
- A wheeled robot that can also hop as high as 1.8 meters. (Exploratory Robot Hops and Rolls, page 13)
- A robot that can move like a snake, stand up straight, and anchor using one end, and manipulate objects with the other. (NASA Gets Snake Robot off the Ground, page 15)
- A demonstration that shows it is possible to make a strip of hybrid gel mimic the movements of a snail, inchworm and snake. (Gel Gains Life-like Motion, page 15)
- An explanation of the many flight tricks of butterflies; these could someday be used by flying robots that weigh under 100 grams. (Butterflies Offer Lessons for Robots, page 16)

Advances in manipulation:

- An explanation of the learning mechanism involved in bouncing a ball on a racket, and a robot that can learn to control a bouncing ball using a racket. (Robots Learn Soft Touch, page 18)
- A robotic hand and arm that boasts 12 degrees of freedom and uses 42 sensors to track the hand's moving parts. (NASA Grasps Intricacies of Human Hand, page 19)
- A vision and vibrating tabletop system that can sort poker chips by color. (Shaky Tabletop Sorts Parts, page 20)
- A material that changes shape in the presence of electricity. (Small Jolts Move Artificial Muscle, page 21)
- A motor that can rotate 360 degrees. (Motor Goes All the Way Around, page 22)

Advances in perception:

- A silicon retina that uses a form of data compression used by biological eyes. (Vision Chip Shines, page 23)
- A low-cost method to measure depth. (Light Show Makes 3D Camera, page 24)
- A flexible tactile sensor skin, University of Illinois, February 2003
- A robot controlled by a network of living rat brain cells, Georgia Institute of Technology, November 2002
- A vision Chip designed to mimic the eyes of jumping spiders (Shaky Chip Makes for Bug-Eyed Bots, page 26)

Advances in navigation:

- A robot navigation system that allows a robot to pinpoint its location using the sound of its voice and microphones spread throughout its environment. (Robot Guided by Its Voice, page 27)
- A system for navigating by sound that uses two microphones and is based on animal hearing, University of Toronto, September 2002

Advances in decision-making:

- A robot scientist that can devise a theory, come up with experiments to test the theory, carry out the experiments, and interpret results. (Robot Automates Science, page 28)

- Multiple mobile robots that are programmed with ant-like behavior and work together efficiently (Ants Solve Tough Problems, page 29)

Advances in coordination:

- A pair of network rovers capable of working together to move objects, drill holes and pitch tents (Cooperative Robots Share the Load, page 31)
- Human-sized, soccer playing robots that get their balance from the bottom half of a segway scooter, and are designed to play soccer in mixed robot-human teams. (Bots, Humans Play Together, page 32)

Advances in human-robot interaction:

- A life-like robot with the persona of an absent-minded professor that can carry on a conversation with a human. (Interactive Robot Has Character, page 33)
- A study that shows how people react to the movements of human-scale robots (Manners Matter for the Circuit-Minded, page 34)
- Software that allows users to control a mobile robot over the Internet using a handheld computer. (Software Eases Remote Robot Control, page 36)

Advances in microrobots:

- A microrobotic arm that has pneumatically-controlled, articulating fingers, University of California at Los Angeles, June 2003
- A robot that weighs less than an ounce and travels on treaded wheels at a top speed of 10 inches per minute. (Tiny Treads Move Miniature Robots, page 37)
- Robot arms two-thirds of a millimeter long that can pick up and move a 100-micron glass bead. (Tiny Robots Flex Their Muscles, page 38)

Advances in self-building/self-shaping:

- Modular robots that can move like snakes and spiders, reconfigure themselves, and whose modules communicate via infrared signals. (Self-Configuring Robots Mimic Lifeforms, page 39)
- An artificial intelligence simulation that evolved the behavior needed for playing Capture the Flag and a team of small robots that used the evolved behavior to play the game in the real world. (Evolution Trains Robot Teams, page 41)
- A system that allows populations of virtual robots to evolve, then uses a rapid prototyping machine to build the evolved body parts. (Robots Emerge from Simulation, page 42)

Mobility

Segway Robot Opens Doors

By Eric Smalley and Kimberly Patch, Technology Research News
November 19/26, 2003

Researchers from Massachusetts Institute of Technology have crossed a robotic arm with the bottom half of a Segway to make a robot named Cardea that can traverse hallways and open doors.

Cardea, named after the Roman goddess of thresholds and door pivots, is the one-armed first prototype of a robot designed to have three arms and the ability to safely interact with humans at eye level.

The Segway scooter platform, with its dynamic balancing abilities, makes the arm practical, said Una-May O'Reilly, an MIT research scientist. "The Segway is... like an inverted pendulum," she said. "Regardless of where the weight is on top of it... the platform is able to move with balance."

This is important because when the robot moves its arm, its center of mass shifts. Without dynamic balancing, a robot that has arms and stands as tall as a human would require a much larger base, said O'Reilly.

Cardea stands about five feet tall and weighs about 200 pounds. It consists of the Segway base, sonar sensors that help in navigation, a pair of cameras that form a rudimentary vision system, and a single arm capable of five degrees of freedom — two at the shoulder, one at the elbow, and two at the wrist. It also has a kickstand in the form of spring-loaded legs that deploy when the robot is in danger of falling, usually due to low battery power.

The prototype is capable of navigating a hall, finding a door and pushing it open, according to O'Reilly. This demonstrates "that we have some of the pieces toward the issues and the challenges of mobile manipulation," she said.

The idea behind building a mobile robot that stands as tall as a human is to explore the ways a humanoid robot can interact with the world, and to make sure it interacts safely, said O'Reilly. The researchers are aiming to give the robot the abilities to recognize whether it's in a room or hallway, recognize and manipulate objects, take instructions, and learn. Given the ability to move around, Cardea can actively explore, she said.

Traditionally, robotic arms have been used to manipulate parts for manufacturing, but factory manipulators operate under a different set of assumptions and within a different realm, said O'Reilly. The environment must be structured in a way that allows them to anticipate, she said. "Parts have to be arranged perfectly so that the robotic arm can interact with them repetitively."

Moving a robotic arm outside a factory setting means teaching the robot to deal with an environment that is not necessarily structured in an organized fashion, said O'Reilly. The present incarnation of Cardea performs a level of mobile manipulation in an unstructured environment, she said. The challenge is making it both safe and able to deal with all the clutter of the real world, she added.

The researchers are aiming to augment the sonar sensors on Cardea's base with a heat-sensing system and improve its vision system with better panning ability and arm-vision system coordination, said O'Reilly. They are also planning to add a robotic hand to the arm, increase the number of arms to three, and give the robot a head, said O'Reilly.

The researchers used a type of robot arm previously designed for MIT's robot Cog. The arm was designed with safety in mind. Robotic manipulators tend not to be sensitive to objects or people, and so are in danger of hurting people or burning out their own motors when they meet an obstruction.

The arm contains a series elastic actuator system that, like biological muscle, provides a buffer between the actuator force and the load it is acting on. An embedded spring system senses forces interacting with the arm. The spring provides feedback about the load and also allows the actuator's motor to gradually apply the force needed to move the load. "We can actually use the spring model to control the arms, and the arms become much safer when they interact with things," said O'Reilly.

The researchers's plans for improving Cardea's arms call for adding two more and also giving the robot a third degree of freedom at each shoulder so that each arm has six degrees of freedom. The three arms will be of different lengths, and will have different end effectors, or hands, designed for different purposes. "You can imagine having different instruments at the ends of the arms, and with that we get more flexibility in terms of what the mechanical system can actually do when it has to interact with the world," said O'Reilly.

Source: Donna Coveney/MIT

This robot, which combines a mechanical arm with a modified version of the Segway scooter, is capable of finding doors and pushing them open.

The current prototype has a simple knob for pushing open doors. The researchers are working on a hand that has three force-controlled fingers. Other hand possibilities include pincers, grippers, flippers and paddles.

The odd number of arms will also widen the robot's interaction abilities, said O'Reilly. "When you've got three arms you can carry something with two and then perform an operation on that object with the third," she said. And while two arms make a single pair, three arms can form three different pairs, she added.

Once Cardea gains a full complement of arms, the researchers will add a more sophisticated vision system that coordinates with the arms, said O'Reilly. "We want to try and understand the various vision-based manipulation problems and how to address them," she said.

Cardea will eventually gain a robotic head similar to the MIT robots Cog and Kizmet, said O'Reilly. "Then we can have a robot that moves around and has to deal with social interaction issues of human-to-robot at human-height level," she said. Cog is a stationary humanoid robot that consists of a head, arms and torso. Kismet is a stationary humanoid robotic head that is capable of facial expressions.

The researchers are also aiming to use Cardea to explore more general notions of behavior, said O'Reilly. The robot will, like its predecessors, learn by exploring its environment and manipulating objects, and interact with humans through facial expressions and tones of voice.

There's also the question of what social character an assistive robot should have, said O'Reilly. "If we were to have a robot [wandering] around the halls and available for assistance... what should the face look like, [and] how should the robot negotiate its interactions, take instructions and show that it's learned or is following them?"

The researchers are also looking at the issue of maintaining a robot that would never really have to power down, O'Reilly said. This would require that the robot understand when it is in need of energy and, for instance, plug itself into the wall, she said. Not having to turn off would be an advantage because complicated robots tend to have time-consuming startup procedures.

MIT's Cardea project is one of a dozen projects at universities and government labs around the country that involve building robots on Segway bases. The projects were initiated under the Defense Advanced Research Projects Agency (DARPA) Mobile Autonomous Robot Software (MARS) program.

The MIT robot and a similar NASA project "make a strong case for the marriage of mobility and manual skill," said Rod Grupen, an associate professor of computer science at the University of Massachusetts, Amherst. Grupen and colleagues are also developing a Segway-based robot under the DARPA program. "These projects... are among the very first to achieve a robot that interacts with people in a human scale environment," he said.

O'Reilly's research colleagues are Rodney Brooks, Paul Fitzpatrick, Lijin Aryananda, Jessica Banks, Aaron Edsinger, Eduardo Torres-Jara, Paulina Varchavskaya, Alana Laferty, Alex Moore, Jeff Weber, Charlie Kemp and Kathleen Richardson. The research is funded by DARPA and by a corporation.

Timeline: Unknown
Funding: Corporate; Government
TRN Categories: Robotics; Human-Computer Interaction; Engineering
Story Type: News
Related Elements: Cardea Web site: www.ai.mit.edu/projects/cardea/

Toy Shows Bare Bones of Walking

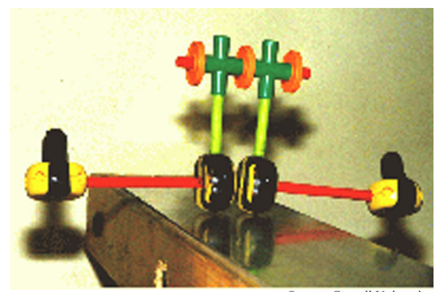
By Chhavi Sachdev, Technology Research News
October 3, 2001

Running, jogging, tiptoeing, and skipping are the motions that set us apart from most of the animal kingdom. We learn to do them on a predetermined schedule and we do them without thinking. We also don't know exactly how we do them.

Researchers at Cornell University have taken a step towards figuring out the mathematics behind the mechanics of human motion by explaining the movement of a Tinkertoy that walks like we do.

The researchers developed the walking toy in 1998, inspired by the passive dynamic walker designed over a decade ago by Tad McGeer, then a researcher at Simon Fraser University in Canada. Passive dynamic walkers are powered and directed only by gravity. The Cornell model is more like a human skeleton than the McGeer model because it moves in all three dimensions and cannot stand up unless it is moving.

After proving empirically that the toy could walk in a stable manner, the researchers set out to find how it worked mathematically.



Source: Cornell University

A tinkertoy walks downhill on its black and yellow feet. The feet are attached to the tinkertoy's hips by orange hinges. On either side of the feet are weights that help it balance. Once the toy stops moving, it falls over.

"Our goal with the mathematical model and associated computer simulations was to find stable periodic walking solutions that could explain the observed behavior of the walking toy," said Michael Coleman, a researcher and lecturer in Cornell's Department of Theoretical and Applied Mathematics.

Most theories of walking rely on neuromuscular explanations. Cornell's approach literally strips the issue to its bare bones. Because the toy walks without muscles, its motion must by controlled by something more basic. The research differs from most biological approaches to understanding locomotion because it "emphasizes the role of pure mechanics in explaining the coordination of animal locomotion," Coleman said.

This appeal to pure mechanics differentiates the work from other engineering approaches that use actuators and computer control to "coax mathematical and physical models to imitate mostly the geometry of walking motions rather than the full dynamics," Coleman said. The tinkertoy's motion is propelled only by gravity, he said.

Models of rigid bodies, whose parts don't change shape, can explain motions at the joints independent of friction between the feet and the ground and between surfaces, he said. Bypassing neuromuscular theories and those of friction, the researchers' math showed that motion is sufficient to keep a body upright.

The tinkertoy's two straight legs are hinged to an axle; each leg has a balancing weight on the side. Its feet are vertical disks. Its steady walk down the ramp is a balance between the kinetic energy gained as the toy falls before its feet collide with the floor, and the energy that is lost in the collisions, said Coleman. Part of the balance comes from automatic steering, or the way the toy moves from side to side as it places each foot. Moving the support point from left to right is also the way people stay balanced when riding a bicycle, walking, or running, said Coleman.

Walking is essentially a smooth, repeated, inverted-pendulum-like three-dimensional motion interrupted by joint and foot collisions, said Coleman. While a bicycle needs both mechanical energy and friction to move, the walking toy needs neither.

Though the Cornell toy can toddle downhill endlessly, it cannot stand if it is not in motion. The same is true of a human skeleton stripped of muscle support. If the muscles and central nervous system were omitted, leaving only enough connective tissue to hold the skeleton at the joints, the resulting collection of bones would collapse while standing still, Coleman said. "So, we imagine that this simple model of the body cannot stand still in any configuration." Walking, however, is a very stable action; small disturbances do not disrupt the gait very much, he said.

The original McGeer walker was less human-like because it had four legs and could only move in a vertical plane. The walker could also stand still with its legs splayed in the fore-aft position, said Coleman. Since McGeer's walkers moved only in a vertical plane with all the motions visible from one side, it is referred to as a two-dimensional model, he said.

Although the Cornell model is closer to a human, there are still several differences. The distribution of mass in the Cornell walkers is not very human-like, Coleman said. The models also do not have an upper body or knees. However, they tie in with human locomotion because they walk in a stable, steady way.

Like a human, the toy moves in three dimension, but because understanding three-dimensional motions can be more complicated than the two-dimensional ones McGeer designed, the researchers chose to use straight legs, point feet, no hip spacing, and no knees in their first attempts. The latest mathematical models have curved feet and spaced hips, but the researchers have not yet added knees, Coleman said.

The work shows how passive dynamics affect stability, said Coleman. This could help in designing stable and efficient legged robots as well as cures and prosthetics for walking ailments. "We expect that our biggest impact will be nearly invisible — as a change in the point of view of people who study human motions and try to correct problems," Coleman said.

"It's a good complement to the more traditional controls approach of trying to make a system do what we want it to, regardless of what it wants to do," said Ben Brown, a project scientist at the Robotics Institute at Carnegie Mellon University. Developing and analyzing simple passive, stable walkers will lead to a better understanding of the fundamental principles of walking and is a step toward finding simple and efficient locomotion methods, he said.

The researchers next plan to build a model that has a gait even more like that of humans, said Coleman. They also plan to see how much locomotion and coordination passive strategies can accomplish and measure the tradeoffs between the key features of correct motions, energetic efficiency, and stability, he said. They will see if an upper body or a head can be added, he said.

"It is possible that adding more human-like anatomical features to our models will result in their having more human-like walking characteristics. But it is likely that these additions will make the walkers unstable and thus needing control like humans have," Coleman said.

Coleman's research colleagues were Andy Ruina and Mariano Garcia at Cornell, and Katja Mombaur from the University of Heidelberg in Germany. They published the research in the journal *Physical Review E.* Andy Ruina received a grant from the National Science Foundation (NSF) and Katja Mombaur received a grant from the University of Heidelberg.

Timeline: now
Funding: Government; University
TRN Categories: Robotics
Story Type: News
Related Elements: Technical papers, "Prediction Of Stable Walking For A Toy That Cannot Stand," Physical Review E, vol. 64, 2001; "An Uncontrolled Walking Toy That Cannot Stand Still," *Physical Review Letters*, vol. 80, 1998.

TRN

Exploratory Robot Hops and Rolls

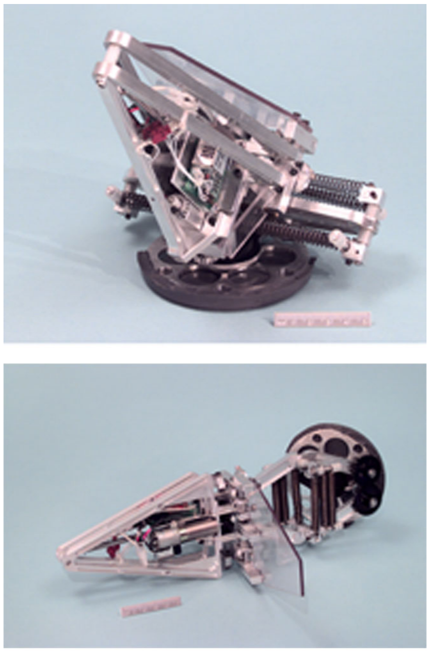
By Ted Smalley Bowen, Technology Research News
December 13, 2000

Getting from point A to point B in the exploration of extraterrestrial terrain is fraught with uncertainty. With that in mind, researchers at NASA's Jet Propulsion Laboratory and the California Institute of Technology have developed a robot capable of both hopping and rolling.

Such robots could be used independently or with larger rover units to map and gather samples from planets or other celestial bodies.

The researchers' third generation frogbot has wheels in addition to its precursor's spring-loaded leg. It can hop to span distances or clear obstacles and roll to reach specific targets.

"It has some wheels on board so that once it hops and lands and crashes and picks itself up, it can locally drive around and almost be like a little miniature rover," said Joel Burdick, a researcher at Caltech's Center for Neuromorphic Systems Engineering.



Source: JPL/Caltech

The frogbot's spring-loaded leg allows it to hop relatively quickly across rough terrain. The latest version, not shown, includes wheels for rolling short distances.

The hurdles presented by navigating remote and unpredictable terrain compound the normal variables facing robot designers, said Paolo Fiorini, a robotics engineer at the Jet Propulsion Laboratory.

"Robotics has always been dealing with uncertainty, but usually it's a very small uncertainty, like you're trying to put a peg in a hole, and perhaps you're missing a little bit, so you put some trick to simplify the problem. But it's some sort of linearization in the neighborhood of your solution. Here, we can have very large uncertainties, so how do we deal with that?"

The roughly 1-kilogram robot uses two or more computer processors and a mechanical timing logic unit to control its functions. It packs a color camera, two dual-axis accelerometers to determine its orientation, and a radio-frequency modem for remote communication.

The designers have also opened up control of the unit's hopping angle, making it possible to adjust the trajectory of its flight. The hopping angle is the angle between the trajectory tangent and the ground, Burdick explained.

"We're able to adjust the hopping angle so we can hop with a very high arc or hop with a very shallow arc, so we can either go out far, or we may want to go high, over a very big obstacle. Or, we can actually shoot ourselves straight up and take a panoramic camera view," he said.

The robot's hopping range is about 1.8 meters in Earth gravity, or about six meters on a low-gravity body like Mars.

There are two ways to design hopping mechanisms, according to Ben Brown, a project scientist at Carnegie Mellon University.

"One is something that sits there and stores up energy and launches itself, like the JPL scheme, and then there's stuff that does more continuous hopping," Brown said.

"The advantage of doing continuous hopping is that you can recover a lot of energy from one bounce to the next. Of course, one of the problems is that you have to control the attitude of the thing when it's flying, so it comes down with the leg pointing down. You also probably have to worry more about what you land on." CMU researchers are working on a continuous hopping mechanism.

The JPL/Caltech researchers are also contemplating a stripped-down version of their robot, according to Burdick. "Imagine you've got a bunch of buttons, which have a basic leg mechanism. You throw a thousand of these things out, and what they do is they hop around and position themselves, and once they get in place the locomotion systems dies, because it's not meant to last a long time."

When the robot stops, "it just sits there as a sensor. You can imagine putting on it seismic sensors, wind sensors, temperature sensors, basically geological types of sensors, so that you could distribute these things out in kind of a network and help to position them using some cheap, onboard locomotion system," Burdick said.

While the project's focus has been technology development in the service of space exploration, there could be terrestrial applications of the basic technology, according to Fiorini.

Such highly mobile robots could be used in search and rescue operations, as listening devices, or in agricultural tasks, such as the precise application of pesticides, he said.

If the technology is selected for use in space, the design will shift to accommodating the demands of space flight, including withstanding multiple g-forces, according to the researchers.

The project is roughly three to five years from producing a mission-ready robot, Fiorini said.

The researchers are testing the third generation frogbot, in anticipation of readying field-test prototypes. Burdick's and Fiorini's colleagues were Eric Hale and Nathan Schara of Caltech. They presented the work, through its second generation, at the 2000 IEEE International Conference on Robotoics and Automation in San Francisco in May.

The work is funded by NASA and the National Science Foundation.

Timeline: 3-5 years
Funding: Government
TRN Categories: Robotics
Story Type: News
Related Elements: Technical paper, "A Minimally Actuated Hopping Rover for Exploration of Celestial Bodies," 2000 IEEE International Conference on Robotoics and Automation in San Francisco in May

NASA Gets Snake Robot off the Ground

By Eric Smalley, Technology Research News
October 11, 2000

A team of researchers at NASA is betting that snakes are a better model than dune buggies for building robots that can explore the surfaces of planets.

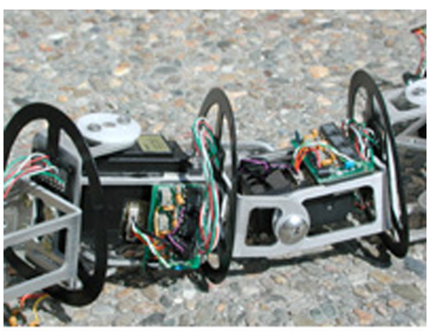
NASA's Snakebot project added sensors and controllers to a multisegment robot developed at the Xerox Palo Alto Research Center.

The NASA researchers are also working on a frame for the Snakebot that features contact-sensing ribs. The sensors will allow the robot to gauge the terrain as it moves.

"If [a] rib is touched anywhere around its perimeter we can figure out where it's being touched and how hard," said Gary Haith, a computer scientist and lead engineer on the project.

The researchers are also adding controllers, or small computers, to each segment so they can move in response to sensor information without having to wait for instructions from the robot's main computer.

"That's like a reflex," Haith said. "We're basically looking at making [the robot] semiautonomous so you can say stuff like 'Go to that rock 10 meters away.' I want to have the snake automatically figure out what kind of surface it's on and transition to the gait that's most appropriate."



Source: NASA

The riblike frame of NASA's third generation Snakebot has contact sensors that will allow the robot to "feel" the ground.

The Snakebot has several advantages over the dune buggy-style rovers currently used by NASA to explore the surface of Mars, said Haith.

"[The Snakebot] is very robust. If one segment [fails] it just means your robot is a little more stiff," he said. The Snakebot is also more stable on uneven terrain and on steep grades, he added.

In addition, the Snakebot can serve three functions: it can move, it can stand upright to gain a better view, and it can fix itself to a surface at one end and manipulate objects with its other end, said Haith.

"So instead of having to send up a rover that has a mast and an arm, you can basically send up one thing that can do all three [functions]," he said.

The Snakebot could be ready for missions in five to ten years, Haith said. The project is funded by NASA.

Timeline: 5-10 years
Funding: Government
TRN Categories: Robotics
Story Type: News
Related Elements: None

Gel Gains Life-like Motion

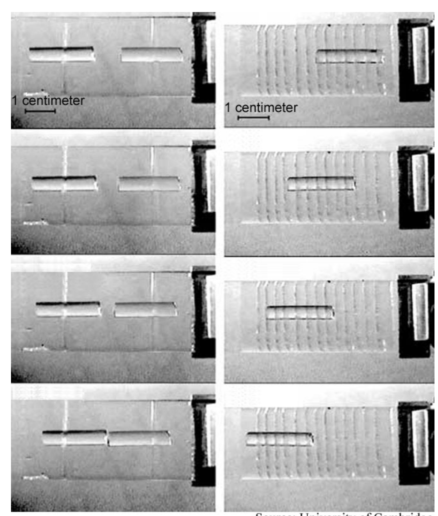
By Kimberly Patch, Technology Research News
December 31, 2003/January 7, 2004

Researchers from the University of Cambridge in England and Lehigh University have shown that it is possible to make a strip of hydrogel mimic the movements of a snail, inchworm and snake.

The ability could lead to new motion techniques for tiny machines, including robots, and for manufacturing processes that involve moving substances across surfaces.

The research also shows that there is an underlying unity in the various forms of movement produced by legless animals.

The researchers' first theorized that the creep of a snail, crawl of an inchworm, and back-and-forth motion of the snake could all be described by one coherent theory. They then found a way to prove it. "After the conceptual breakthrough, the main challenge was thinking of the simplest experimental setup to realize it," said Lakshminarayanan Mahadevan, who is now a professor of applied mathematics and mechanics at Harvard University.



Source: University of Cambridge

The left column of pictures shows a pair of gel strips moving toward each other; the pictures on the right show a gel strip moving from right to left.

The researchers tested the theory by cutting scales into the bottoms of 2-centimeter-long strips of acrylamide hydrogel and placing them on a vibrating table. They were able to cause the strips to mimic the three types of legless locomotion by varying the angle of the scales and the direction of vibration. The experiment shows that "a simple idea can explain the various regimes of locomotion," said Mahadevan.

Most work on microelectromechanical devices that has to do with moving objects around has focused on microfluidics — controlling small quantities of fluid, said Mahadevan. The hydrogel work shows that soft solids can be moved around relatively easily using a fairly simple process, he said.

The remaining challenge is to find a way to provide the vibrations internally, said Mahadevan. "This can probably be done with a simple onboard engine such as a mechanical-active gel that responds to external actuation [from] electromagnetic or chemical fields" or temperature, he said.

Putting the power on-board would allow for a feedback loop that allows the engine to respond to the way the gel deforms, or bends, according to Mahadevan. Feedback like this allows organisms to respond to external stimuli by changing gaits.

The researchers are working toward a more quantitative understanding of the mechanisms involved in the gel movement in order to figure out how to optimize the motions, said Mahadevan.

The next step is to understand optimal gaits and the transitions between them, and to explore additional gaits like side-winding, slide-pushing and concertina motion, according to Mahadevan. Sidewinder snakes twist and turn to move. "Concertina motion is when the snake literally squeezes itself into the shape of a concertina while pushing against the side of a tube and then alternately drags itself or pushes forward," he said.

The gel devices could be used in practical applications in the next couple of years, said Mahadevan. They could be used in microelectromechanical systems, and robots that inspect crevices and other hard-to-get-to places, he said.

Mahadevan's research colleagues were Manoj Chaudhury and Susan Daniel. The work appeared in the December 15, 2003 issue of *Proceedings of the National Academy Of Sciences*. The research was funded by the Office of Naval Research (ONR).

Timeline: 2 years
Funding: Government
TRN Categories: Materials Science and Engineering; MicroElectroMechanical Systems (MEMS)
Story Type: News
Related Elements: Technical paper, "Biomimetic Ratcheting Motion of a Soft, Slender, Sessile Gel," *Proceedings of the National Academy Of Sciences*, December 15, 2003

TRN

Butterflies Offer Lessons for Robots

By Kimberly Patch, Technology Research News
February 12/19, 2003

It turns out that butterflies' fluttering is neither random nor clumsy.

Researchers from Oxford University in England have devised a method of studying the way butterflies fly, and their initial results show that the insects have many more tricks of flight than they get credit for.

The researchers trained red admiral butterflies to fly between artificial flowers in a wind tunnel, and recorded the way air flowed around their wings using smoke and high-resolution cameras. The work provides fodder for researchers working on insect-sized flying robots.

Previous studies have revealed a couple of secrets of insect flight. Researchers from the University of Cambridge in England working with tethered hawkmoths and flapping robots showed that wing movement creates columns of spinning air, or vortices, above the leading edges of wings, which provides the lift needed to fly. A vortex above a wing can create as much as a twofold increase in lift.

And researchers from the University of California at Berkeley working with robotic fruit fly wings discovered that fruit flies capture turbulence from their own wakes to increase lift.

These results put insects in two camps - large insects that produce vortices above the leading edges of their wings to create lift, and small insects that instead hover or fly slowly enough to capture lift as their wings pass back through the wakes of disturbed air they leave behind.

The free-flight studies proved butterfly flight is much more complicated, according to Robert Srygley, a professor of behavioral ecology at Seoul National University in South Korea and a research associate at the University of Oxford.

Free-flying butterflies "use all of the known mechanisms to enhance lift — wake capture, leading-edge vortex, clap and fling, and active and inactive upstrokes — as well as two mechanisms that had not been postulated, the leading-edge vortex during the upstrokes and the double leading-edge vortex," said Srygley.

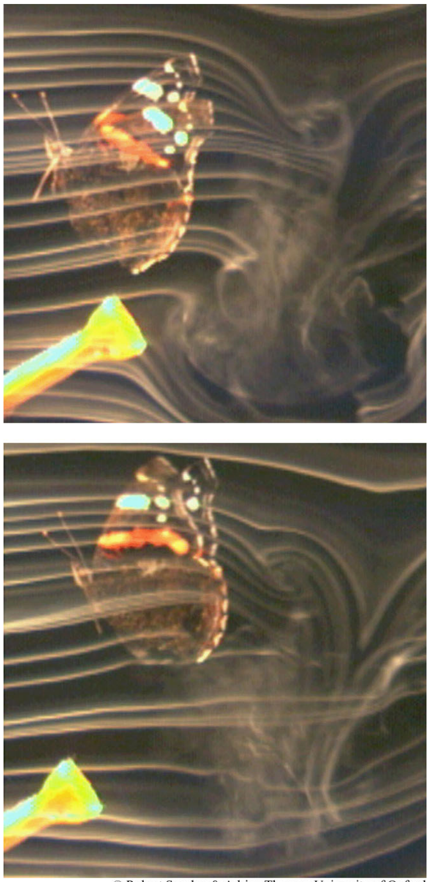
The research showed that butterflies create vortices and double vortices above the leading edges of their wings by varying the twist and speed of their strokes to make sudden changes in pitch.

They use vortices shed from the wing's trailing edge — the wake — recycling their own energy to further increase lift. They also use a clap-and-fling mechanism to produce opposite vortices on each wing, which also contributes lift. The red admirals do this by touching their wings briefly, then rapidly separating them. And they use a mix of active upstrokes, which generate lift, and inactive upstrokes, which do not.

The basic butterfly stroke is not smooth. Going into a downstroke each wing is up and back, with the wings' leading edges pointing foreword. As the wings go down and foreword they also continuously rotate, changing the wing angle. Just before the upstroke the butterfly quickly twists its wings so the leading edge points backwards. On the upstroke the wings go up and back and again continuously rotate; there's another quick rotation at the end of the upstroke to position the wings before the next downstroke.

The brief stops before each downstroke and upstroke, and accelerations and decelerations between strokes vary the airflow considerably.

The researchers' smoke patterns showed that butterflies often used different aerodynamic mechanisms in successive strokes.



© Robert Srygley & Adrian Thomas, University of Oxford

In the top image, the red admiral butterfly is at the top of its upstroke. The horizontal ring in the smoke to the right of the yellow artificial flower is the vortex produced by the previous downstroke. In the bottom image, the vortex is breaking up after the butterfly has passed its wings through it in order to recapture some of its energy.

The familiar, random-looking fluttering of butterflies is really due to the animals using a wide variety of aerodynamic mechanisms as they take off, maneuver, maintain steady flight, and land, said Srygley.

In general, the butterflies made more use of vortices during acceleration, Srygley said. "The leading-edge vortex is most pronounced when the red admiral butterflies are accelerating; when maintaining a steady speed [it] became less pronounced," he said.

This makes sense given the drag that must arise from altering the flow of air from across the top surface of the wing to form a vortex that moves towards the wing tip, he said. "Insects are probably trying to minimize the drag during steady foreword flight, and restrict use of the leading-edge vortex to periods of acceleration and maneuvers," he said.

It is interesting that the butterflies show various wing aerodynamics during different modes of flight, said Robert Michelson, a principal research engineer at the Georgia Tech Research Institute. And it's significant that the butterflies were not tethered, but allowed to fly freely.

The work runs counter to a study at Cambridge University in England that showed that the leading edge vortex varies in diameter as it moves out along the wing during the flap, said Michelson. "This study seems to counter the notion of diameter change and span-wide flow," he said. "A third validating study would be nice to help resolve who is right."

Michelson's research includes a small, flapping wing robot dubbed Entomopter. Flapping wing aerodynamics is not well understood, said Michelson. "This study adds to the rather meager body of knowledge," he said.

Controlling insect wings "is physically complex, difficult to miniaturize, and... very power hungry," he added.

The study improves the understanding of aerodynamics at a scale where engineers have not yet built many systems, but where nature has a great diversity of designs, said Ron Fearing, a professor of electrical engineering at the University of California at Berkeley.

The results could be useful for robotic fliers weighing between 100 milligrams and 10 grams, he said. "If the aerodynamic efficiency were significantly higher than fruit fly kinematics, it would likely be worth using a more complicated wing drive mechanism," he said. The mechanical difficulty of using the more complicated butterfly kinematics and the precision of control required has to be evaluated, he added.

There is a lot left unknown about insect flight, said Srygley. "Just about every flight mechanism in the insect world remains unexplained," he said.

The basic theory for biological flight is based on propeller theory. This theory adapted to flapping wings does a reasonable job of explaining bird flight, said Srygley. "However, it does not explain all the lift required for an insect to fly."

The researchers next step is to explore the diversity of insect flight using the free flight study method, said Srygley. "We've just opened the door on free flight studies, and of course much remains to be discovered."

The research could find use in robotics within a decade, said Srygley. "I would expect that we will see flapping [robots] the size of butterflies or hawk moths with reasonable flight durations [and] distances in five to ten years," he said.

Flying robots could explore volcanic vents, assess stresses on bridges or skyscrapers, or other planets, said Srygley. "Hundreds of small robots could be lifted into space to probe planetary surfaces rather than lifting a single crawling robot," he said. As long as the planet to be explored has an atmosphere, more area could be covered using flying robots, he said.

Srygley's research colleague was Adrian L. R. Thomas of the University of Oxford. The work appeared in the December 12 issue of Nature. The research was funded by the British Biotechnology and Biological Science Research Council (BBSRC).

Timeline: 5-10 years
Funding: Government
TRN Categories: Applied Technology; Biology; MicroElectroMechanical Systems (MEMS); Robotics; Physics
Story Type: News
Related Elements: Technical paper, "Unconventional Lift-Generating Mechanisms in Free-Flying Butterflies," Nature, December 12, 2002

TRN

Manipulation
Robots Learn Soft Touch

By Kimberly Patch, Technology Research News
February 28, 2001

Learning to bounce a ball on a tennis racket may seem easy, but when you dig into the details of the process in order to, say, build a robot that can learn to do it too, it becomes obvious that the task is fairly complicated.

The mathematics involved in bouncing a ball on racket are nonlinear, meaning the problem cannot be solved simply. The bouncing ball is actually a chaotic system that has a lot in common with complicated systems like liquid flow and weather.

It doesn't take a mathematician to learn the task, however. Give a human instructions to bounce a ball on a racket and before long the human will be controlling the ball in an efficient, stable way without having to know why.

A team of researchers from Pennsylvania State University, the University of Southern California, and the University of São Paulo are looking into the principles that allow humans to so easily control complicated systems. These principles could eventually lead to more independent robots and better artificial limbs.

According to the researchers, the secret to the particular task of bouncing a ball is to slightly slow down the upward motion of the racket just before it hits the ball.

Humans do this instinctively even though it would be a little more efficient to hit the ball when the racket is moving upward at its greatest velocity, or speed. Slowing the racket down, however, makes the system more stable, which in turn makes it easier to control.

"The acceleration of the racket needs to be within a range of values in order to ensure dynamic stability that then does not require explicit correction," said Dagmar Sternad, an assistant professor of kinesiology at Pennsylvania State University.

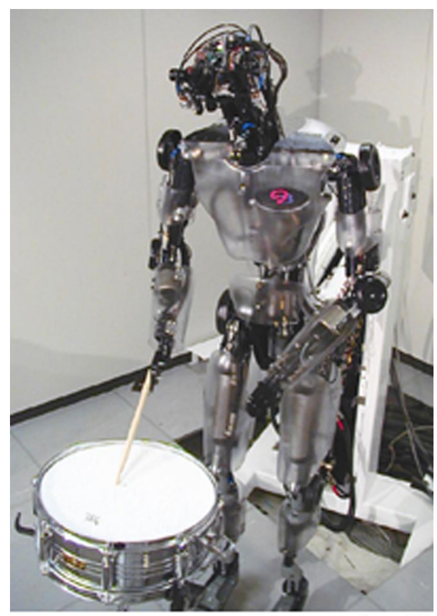
Sternad likens the more stable system to a ball resting at the bottom of a funnel. If the ball is disturbed it will tend to fall back to the stable point at the bottom of the funnel.

Although conventional wisdom says vision is our dominant sense, the research showed that people find the right way to bounce a ball on a tennis racket largely by feel, said Sternad. "Conventionally we always look at visual information and think that that is the dominant source of information. In this case it is not. Dynamic stability is better exploited when we have haptic, or kinesthetic information as opposed to visual information," she said.

Following the dynamic stability principal allows the human body to do a task more efficiently than achieving it using feedback control, where the brain and muscles communicate via the nervous system and the brain directs every muscle movement based on what happened the instant before.

The dynamic stability principal is a useful discovery, said Andy Ruina, professor of theoretical and applied mechanics, and mechanical and aerospace engineering at Cornell University. "[It] shows her that people do actually use these no-feedback mechanisms, even while they do use feedback. It seems from their experiments that people use a higher level feedback — learning — to find motions that require less explicit short-term feedback," he said.

Although the most common way to program a robot is to use feedback to control all its movements in two-millisecond increments, an approach growing in popularity and supported by the research is to "only provide control over things you care about and not worry about tracking things in time in detail," said Ruina. "Who cares, for example, where [the] racket is when it is not in contact with [the] ball," he said.



Source: USC

This humanoid robot retains better control of the drum sticks by slowing them slightly just before impact, a principal that humans learn instinctively.

Sternad's research partner Stefan Schaal is taking the research in that direction. "Our key interest is really what algorithms the brain uses [to create] human motor control... and how this can help to make artificial systems more intelligent," said Schaal, assistant professor of computer science and neuroscience at the University of Southern California. "People have looked at [bouncing a ball on racket] before in robotics and they have... developed really complicated control systems which proved to be stable... but they were very inefficient in comparison to the one we found," he said.

This is because controlling a robot using feedback is a large task when the movement is nonlinear and the possibilities nearly endless. Using the dynamic stability principal opens up "a totally different way of programming. It turns out that in these types of systems the environment can drive your movements — it becomes a little bit like a reflex," Schaal said.

Using the dynamic stability principal he and Sternad extracted from human behavior, Schaal has given his humanoid robots the ability to more efficiently "bounce balls, juggle balls [and] synchronize drumming to an external drummer," he said.

The researchers are ultimately looking to identify the underlying mechanisms that allow humans to find and use many basic movement principles, said Schaal. "We believe that human movements [in general] are very simple building blocks which can be described mathematically and if you put them together you can build very complicated movements," he said.

Schaal likened the process to a conductor directing every person in an orchestra, but relying on individual players to know the details of playing their instruments.

Understanding the way humans achieve complicated movements will eventually allow machines to "become more autonomous and create their own movements — basically become more humanlike," he said.

The same principles could also eventually lead to better artificial limbs, said Schaal. "You might even be able to use it in neural prosthetics [where] an impaired arm might be revived by interfacing computers to the musculature and then creating natural movement based on this kind of theory," he said.

The researchers are currently setting up a virtual environment in order to study what happens when people get conflicting kinesthetic and visual information. That environment will also allow them to more closely examine how people deal with changes in the system, said Sternad. "We want to... see how we deal with perturbation and how does it correct itself," she said.

They are also looking into exactly how the human muscle system carries out the principles. This is a difficult problem because the muscle system can carry out a given task in many different ways, said Sternad. "We're looking at the organization of the arm — that is how do our arm, shoulder, elbow and wrist joints and [the] many muscles that move [them] get organized in their infinitely many possibilities in order to obtain this particular variable," she said.

Sternad's and Schaal's research colleagues were Marcos Duarte of the University of São Paulo and Hiromu Katsumata of Pennsylvania State University. They published the research in the January, 2001 issue of Physical Review E. The research was funded by the National Science Foundation (NSF).

Timeline: Now
Funding: Government
TRN Categories: Chaotic Systems, Fuzzy Logic and Probabilistic
Reasoning; Robotics
Story Type: News
Related Elements: Technical paper, "Dynamics of a Bouncing Ball in Human Performance," Physical Review E, January, 2001

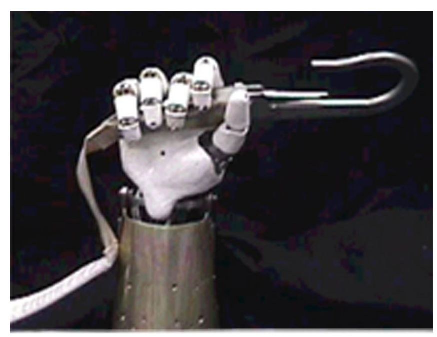
NASA Grasps Intricacies of Human Hand

By Eric Smalley, Technology Research News
June 28/July 5, 2000

Robotic hands have been around for decades but they usually bear little more than a passing resemblance to the real thing. Now NASA researchers have raised the bar with a robotic hand that closely mimics the inner workings of the human hand.

The hand, part of the ongoing Robonaut project, is designed to use the tools and handholds astronauts use during space walks. This purpose, more than aesthetics, led the researchers to copy the human hand as closely as they did, said Chris S. Lovchik, an engineer at NASA's Johnson Space Center in Houston.

"The more you begin to look at tool use, [you find that different tools] involve different portions of the hand," he said. For example, the palm of the Robonaut hand had to be accurately modeled in order for the hand to grasp a screwdriver in alignment with the roll of the arm, he said.



Source: NASA
The hand of NASA's Robonaut closely mimics the human hand in order to use tools and handholds designed for astronauts.

The device is a right hand attached to a wrist and forearm. It has 12 controlled degrees of motion and 42 sensors for tracking the position and velocity of the hand' s moving parts. The researchers are adding tactile sensors.

"It's one of the best [robotic hands] that I've seen," said Reid Simmons, a senior research scientist at the Robotics Institute at Carnegie Mellon University. "It's really quite an amazing piece of work. It's got very good dexterity. It's amazing how compact it all is."

The Robonaut system, which will have a torso, two arms and a head, is designed to be controlled by a human operator. "The overall objective is essentially to create a surrogate for the astronauts," Lovchik said. Researchers are programming primitives, or sets of commands for simple actions, that make the hand easier for the operators to use. For instance, you don't think about how to draw a circle because your brain learned the primitives for drawing a circle in early childhood.

The researchers plan to automate simple tasks like grasping and could eventually make the hand fully automated, according to Lovchik. Fully automating the hand will be a major project, according to CMU's Simmons.

"A lot of what [humans] do very well is very fine force feedback control," Simmons said. "If you're putting and nut on a bolt you can feel when it's getting stuck and when it's too tight, and you can compensate for that. That type of [control] is beyond current state-of-the-art."

Robonaut could be ready for space missions in five years, according to Lovchik. Funding for the project comes from NASA and the Department of Energy.

Timeline: 5 years
Funding: Government
TRN Categories: Robotics
Story Type: News
Related Elements: None

TRN

Shaky Tabletop Sorts Parts

By Kimberly Patch, Technology Research News
October 25/November 1, 2000

If you're willing to wait half a minute, Dan Reznik's vibrating table will pass you a glass of champagne all by itself.

The Universal Part Manipulator is a table outfitted with flexible legs and four motors that gently vibrate to move objects around the surface. An overhead camera allows a computer to keep track of what's on the table and coordinate movements. The part manipulator's most complicated task to date is sorting poker chips by color.

The inspiration for this device was a computer's 'clean up desktop' button, said Dan Reznik, a postdoctoral student at Berkeley.

"With Windows... if you have folders scattered all over the place you can hit a button... and all the folders go neatly to grid points and get neatly rearranged. What if you could build a device that [automatically rearranges] objects in the physical world?" Reznik said.

The table has pairs of motors attached to two consecutive sides. This configuration allows it to move in three types of ways within the plane of the table: font to back using the motors on one side of the table, side to side using the motors on the consecutive side, and rotating when motors on the same side of the table move in opposite directions. "The motion is always horizontal, there's no up and down motion," said Reznik.

Reznik likens the vibrating motion to a foot massage machine. "If you put your hand on the table you can feel... a very low amplitude vibration," he said.

The table is made of an aluminum honeycomb material used for airplane floors because it is light and sturdy.

"You want [it] to be light because there's a motor that is pushing the table around — the lighter the table the smaller your motor can be," Reznik said

The researchers developed motion primitives, or algorithms to control the motors. The basic movement moves objects forward one centimeter per second. "It executes a vibration in one direction very quickly and then comes back in the opposite direction a little slower," allowing the object to slip forward slightly, said Reznik. If the vibration is fast enough, the objects appear to be moving forward continuously.

Currently, the table shuffles objects around fairly slowly. If it is moving one object at a time, the object will move one centimeter per second. If the table is actively moving more than one object to different places on the table, each object will travel a fraction of that centimeter per second. For instance, if the table is trying to move three different poker chips to different places on the table, each chip will move at one-third of a centimeter per second.

The slowdown happens for the same reason it takes a juggler more time to go through a juggling cycle as the number of juggled objects grows, said Reznik. "It would take a longer time for the juggler to cycle back to bottle No. 1 — the same thing here. It is a kind of juggling motion... and as you add more objects the table spends more time juggling all the objects at the same time," said Reznik.

The table can move several objects at full speed if it groups them, however, and it can move one object at full speed while keeping others in place.

There was both a trick and a hard part to the project, said Reznik. The trick was realizing that it was possible to move one object on a plane while keeping others in the same place.

The motion primitive that accomplishes this applies a motion waveform to the table centered on the object to be moved. This vibration causes all objects on the table to move, but at the end of each millisecond long movement only the one object will inch forward, while the others will end up back where they began.

The difficult part of the project was integrating several technologies, said Reznik, pointing out that computer science, mechanical design and electronic design were all involved.

The work is impressive, said Matt Mason, professor of computer science and robotics at Carnegie Mellon University. "There have been a number of robotics researchers working on what we call nonprehensile manipulation or graspless manipulation... Reznik's work takes this idea to a very elegant extreme by moving several objects at once, giving each object an independent motion. His work combines an elegant use of planar kinematics with a creatively engineered use of friction to provide the motive power."

The work neatly sidesteps the difficult robotics problem of designing a general-purpose grasping hand, Mason said. "The hand is just a flat table, which fits all parts," he said.

There are issues still to be addressed, he added. For instance, the universal part manipulator can't handle round objects, and is fairly slow. "It might make sense to think about having more than one plate ... [or] to consider other ways of exciting the plates, or using shapes other than flat plates," said Mason.

Reznik is currently working on speeding the movement of objects on the table by about three times and allowing it to handle a wider variety of objects like pliers, computer chips, CD cases, books, and wine bottles. "We're manipulating full wine bottles right now. [They're] more unstable objects to manipulate then a glass because the bottle itself is taller," Reznik said.

Eventually, he plans to produce specific demos of more interactive tables like a desk that straightens itself, or a kitchen table that knows where the salt shaker belongs. "I would either be competing with the table to move [objects] to a specific spot or be aided by the table," said Reznik.

Other future possibilities include a warehouse with a smart floor that organizes boxes, or an entertainment application that moves people around.

The table project should produce something practical within two years, said Reznik. "I think a couple years is a good horizon for something commercial to pop out of this research," he said.

Reznik is continuing to work on the vibrating table as postdoctoral student at Berkeley, but is also employed by Siemens.

Reznik's research colleague is John Canny of Berkeley. They have submitted a technical paper titled "C'mon Part, Do the Local Motion," to the IEEE Conference on Robotics and Automation scheduled for Seoul in May, 2001. The research was funded by the National Science Foundation (NSF).

Timeline: 2 years
Funding: Government
TRN Categories: Applied Computing
Story Type: News
Related Elements: Photo 1, Photo 2; Technical paper "C'mon Part, Do the Local Motion," submitted to the IEEE Conference on Robotics and Automation scheduled for Seoul in May, 2001; Technical paper "Building a Universal Part Manipulator," IEEE Conference on Robotics and Automation in May, 1999 in Detroit; Reznik's demos www.cs.berkeley.edu/~dreznik/UPM2000/experiments.htm

TRN

Small Jolts Move Artificial Muscle

By Kimberly Patch, Technology Research News
October 2/9, 2002

Electroactive polymers are plastics that expand or contract in the presence of an electric field. Cycle through these shape changes and the materials become actuators or motors that work much like biological muscles. Pump electrons into these polymers, and they can store this electricity.

There are a couple of drawbacks to today's electroactive polymers, however. They require a considerable amount of voltage to change shape. And although some polymers store a useful amount of electricity, finding others that store more would mean being able to make smaller gel-type batteries.

The key is finding materials that have a high dielectric constant, or ability to resist the flow of electric charge. Current practical electroactive polymers like those used in batteries have dialectic constants of around five.

Researchers at Pennsylvania State University have increased the number more than two orders of magnitude with a new composite electroactive polymer that boasts a dielectric constant as high as 1,000.

There are two major uses for the new material, said Qiming Zhang, an engineering professor at Pennsylvania State University. It could be used as artificial muscles or motors that do not have any moving parts, and in super-strength capacitors, or batteries, that can store a lot of charge in a relatively small amount of space.

"When you put it in an electric field it changes shape, so it can push and pull, so it's a kind of motor," said Zhang. Such a simple motor has some interesting advantages, he said. "If you cut a [conventional] motor into two pieces, the motor will not work. But this one — if you cut it into two pieces, potentially each piece will be working," he said. It is also easy to make very small motors this way. Lower-voltage materials could be used more safely in medical applications and to activate moving parts toys.

The advantage of using a material with a higher dialectic constant for batteries is that the batteries can be made smaller. If the material has a dialectic constant a thousand times higher than the regular polymer, the battery volume will be a thousand times smaller, said Zhang. This could make for much better electric cars, he said. "If you want... a car which is very compact, you don't want a battery as big as your house."

In order to hold a charge, a material must block electric current from flowing. This is somewhat like introducing water into a pipe, then blocking it on both ends, said Zhang. If there are two blocked points the water can slosh back and forth in the close section of pipe, but can't flow through. "The charge of the electrons inside the molecules can move within those molecules, but they will not be able to escape," he said. "The dialectic constant is... a kind of measure of how much charge you can move inside the polymer chain. If you can move a lot, you have a high dialectic constant."

The shape change happens because, instead of conducting current, the polymer molecules store the energy by changing the length of the chemical bonds that hold the long, chain-like molecules together. "All the chemical bonds are formed by electrons, so if you can move electrons around you can also change the bonds in length... and the molecule shape can change," said Zhang. "When the polymer changes in shape, you can get a lot of volume change."

The researchers made their more sensitive shape-shifting material by starting with polymer that has a dielectric constant of 60, and adding grains of a second material to the matrix of long, flexible polymer chains. This second material, copper-phthalocyanine, has a dielectric constant in the millions, but is not flexible. The researchers were able to incorporate the tiny grains into the polymer matrix without making the material much less flexible.

Previous attempts at adding materials to polymers to increase their dielectric constants used tiny grains of ceramics, which have higher dialectic constants than copper-phthalocyanine, but made the polymer too stiff. Copper-phthalocyanine is an organic molecule that's also used as a dye, and as a main ingredient for organic transistors.

The research is excellent, and the material has great potential, said Yoseph Bar-Cohen, a senior research scientist at NASA's Jet Propulsion Laboratory and an adjunct professor at the University of California at Los Angeles.

One limitation of today's electronic-type electroactive polymers is it takes a very high electric field to actuate them, said Bar-Cohen. "Having to use very high voltage carries risks to the users," he said.

Lower-voltage electroactive polymer materials should find numerous applications, including toys, said Bar-Cohen. Miniature electroactive polymer actuators could also be used in microfluidic devices, which move and mix small amounts of fluids, he said.

The researchers' next step is to use tinier grains of copper-phthalocyanine to boost the dialectic constant. It would be "the same material, but we want to make the filler much smaller," Zhang said. Much smaller particles means more surface area and so more boundaries that will act as barriers to block current, he said. It may be possible to boost the dialectic constant to 5,000 or even 10,000, said Zhang.

The material could be ready for practical use as an artificial muscle material within three years, and for other applications within five years, said Zhang.

Zhang's research colleagues were Hengfeng Li, Martin Poh, Feng Xia, Z.-Y. Cheng, Haisheng Xu, and Cheng Huang. They published the research in the September 19, 2002 issue of *Nature*. The research was funded by the National Institutes of Health (NIH), the Defense Advanced Research Projects Agency (DARPA), and the Office of Naval Research (ONR).

Timeline: 3 years, 5 years
Funding: Government
TRN Categories: Chemistry; Energy; Materials Science and Engineering;
MicroElectroMechanical Systems (MEMS); Robotics Story Type:News
Related Elements: Technical paper, "An All-Organic Composite Actuator Material with a High Dielectric Constant," *Nature*, September 19, 2002

Motor Goes All the Way Around

By Eric Smalley, Technology Research News
January 31, 2001

Imagine an oversized trackball that moves by itself and you've got the basic idea of a spherical motor that could lead to better robot arms and even cars that slide sideways into tight parking spaces.

Although spherical motors are not new, most have limited ranges of motion. Researchers at Johns Hopkins University have developed a more useful version with an unlimited range of motion.

Source: Keith Weller, Johns Hopkins University

Carefully controlled electromagnets in the base of this spherical motor control the rotation of the ball.

"We developed the first spherical motor that can turn completely around," said Gregory S. Chirikjian, an associate professor of mechanical engineering at Johns Hopkins University.

The motor looks like a basketball sitting in the open end of a cone. The inside of the ball is lined with common, permanent magnets, and the inside of the cone is lined with electromagnets.

"We sequence the electromagnets turning on and off, and that attracts the permanent magnets inside the ball to cause the ball to turn," said Chirikjian. "In addition, we've developed an encoder, which is a way to determine [the] orientation of the ball."

The current protype has a 12-inch-diameter ball. The design could be scaled down to one inch, said Chirikjian.

One motivation for developing the spherical motor was to build more efficient robot arms, he said. Most robot arms are made of motorized joints that can only move along one axis, requiring as many as six to give the arm full range of motion, Chirikjian said.

Source: Keith Weller, Johns Hopkins University

The ball is lined with a series of permanent magnets.

"Instead of having many one-degree-of-freedom motors that turn around one fixed axis, you could have relatively few ball-like motors," he said, noting that the human arm has two ball joints, the shoulder and wrist, and one single-axis joint, the elbow.

The spherical motor could have a wide range of applications, said Chirikjian. One possibility is a camera mount. "You could put a camera on the ball and this would be a way to move the camera in any direction," he said.

It could also power a computer mouse that could move itself. "The motor could... push the user over here, over there, to influence the behavior of the user and provide feedback," Chirikjian said.

If they were large enough, the motors could also be used as both wheels and motors for an omnidirectional vehicle, he said.

There are no technical hurdles to implementing the spherical motor, though it will likely be five years before commercial applications are likely, said Chirikjian.

Chirikjian's research colleagues were David Stein and Edward R. Scheinerman. The research was funded by the National Science Foundation.

Timeline: Now, 5 years
Funding: Government
TRN Categories: Robotics
Story Type: News
Related Elements: None

TRN

Perception

Vision Chip Shines

By Eric Smalley, Technology Research News
September 10/17, 2003

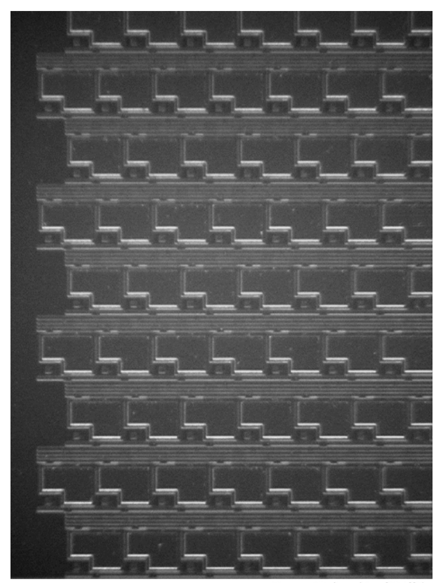
The video cameras and complicated image processing software that are used to give machines the ability to see are relatively bulky and expensive. Many research teams are working toward a better solution — eyes-on-a-chip.

Researchers from the State University of New York at Buffalo and Stanford University have built a silicon retina that uses a timing signal to mimic a form of data compression performed by biological eyes, and transmits high-speed optical rather than electrical output.

The silicon retina could be used to give small robots a better understanding of their visual environment, according to Albert Titus, an assistant professor of electrical engineering at the State University of New York at Buffalo. The electronic retina could also be used in smart sensors and remote monitoring cameras, where its ability to sort out important information would allow reduced amounts of data to be analyzed, transmitted and stored.

Like its biological forerunners, the electronic retina processes the larger amount of data that makes up an image in order to transmit a smaller amount of key information. The silicon retina provides information about the edges of images rather than a whole picture. Edge information is usually sufficient for detecting and tracking objects.

The device's pixels are an array of light detectors made from metal oxide semiconductor. The array takes in an image, processes the information, and passes the compressed output to a liquid crystal spatial light modulator on the chip. Spatial light modulators pattern light, in this case allowing it through in positions corresponding to pixels that generate an electrical "on" signal.



Source: University of Buffalo

This chip is an artificial retina. The larger rectangles are mounts for tiny liquid crystal light modulators that control the chip's optical output. The smaller rectangles are light detectors.

The spatial light modulator enables output from each receptor, or pixel, to be transmitted optically, which allows the process to take place nearly in real-time. "Optical output... allows for maximum parallelism of the data output, and requires no wires to send the data," said Titus.

Otherwise, with electrical output, an array of 4,096 pixels would require 4,096 output wires from the chip, or it would have to slow down the process by sending more than one output per wire, said Titus. "These are both unrealistic approaches," he said.

Biological retinas use two types of light receptor cells — rods and cones — to convert optical energy into electrochemical responses that can be processed by nerve cells. Cones are sensitive to color, and work best in bright light. Rods allow for vision in dim light.

Three other types of cells — amacrine, bipolar and horizontal — work together to share signals between receptors, and to transmit the signals to nerve cells. The result is the light pattern the retina picks up gets transformed, or filtered, into a more concise set of information for the ganglion cells that make up the optic nerve, said Titus. "There are anywhere from 10 to 1,000 [times] fewer ganglion cells than receptors, so there is a significant amount of data compression that occurs between the light input and what is transmitted to the brain," he said.

One form of retinal data compression is "a response that corresponds to the edges of objects," said Titus. "If you break an input image into objects represented by just their edges — changes in intensity — then you remove a lot of information from the image, but you still have quite a bit of information about the scene," he said.

The researchers' design models the function of the receptors and the bipolar, amacrine and horizontal cells, said Titus. "Our silicon retina produces information about the edges and performs edge enhancement based on motion," he said.

Edge detection is a common capability of artificial retinas. The researchers' design is unique because it uses a clock signal to synchronize the pixels, which allows the chip to work efficiently, according to Titus. A pixel in the artificial retina is about 10 times faster than a photoreceptor in a biological retina, so it can perform several operations for every photoreceptor operation, said Titus. This helps the artificial retina perform edge detection using a relatively small number of pixels, he said.

The chip also draws very little power. Each cell requires less than one ten thousandth of a Watt to turn on and off at speeds of a few kilohertz, or thousand times a second.

The researchers have built a prototype that contains 256 pixels, and are working to make a more complete silicon-based system that can be used in autonomous robots and smart sensors, said Titus. They're also aiming to use the silicon retina in cameras for remote monitoring for safety, identification and biometrics purposes, he said.

The researchers are also working on artificial retinas that do more than just edge detection, said Titus.

The silicon retina could be used in practical applications within one to five years, according to Titus. Applications using optical output will have to wait 10 years or so until optical interconnects are available for interchip communications, he said.

Titus's research colleague was Timothy J. Drabik. The work appeared in the August, 2003 issue of Optical Engineering. The research was funded by Displaytech, Inc.

Timeline: 1-5 years, 10 years
Funding: Corporate
TRN Categories: Computer Vision and Image Processing; Optical
Computing, Optoelectronics and Photonics
Story Type: News
Related Elements: Technical paper, "Optical Output Silicon Retina Chip," Optical Engineering, August, 2003

TRN

Light Show Makes 3D Camera

By Kimberly Patch, Technology Research News
May 5/7, 2003

True three-dimensional movies, where projected characters look like they are occupying the same room as the audience, require a couple of new technologies: a projection system that can put the many dots of color that make up the three-dimensional image in the right places at the right time, and a camera that can capture the action in the first place.

Researchers from the University of Kentucky have come up with a relatively low-cost method to measure depth using a single camera. The scheme involves shining a light pattern onto an object, and gaining depth information from the way the object distorts the pattern.

The researchers' depth camera prototype is made from off-the-shelf parts worth about $4,000, Chun Guan, a researcher at the University of Kentucky. "A system well below $1,000 is certainly possible," given mass production, he said.

The camera could lower the cost of computer vision systems that enable computers to locate people and sense gestures, and could eventually be used to capture the depth information needed for three-dimensional videos.

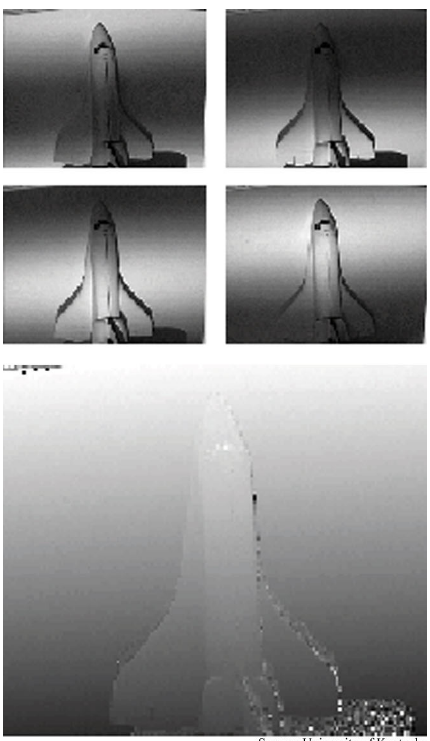
Existing computer vision systems that identify a person's location and read gestures use several cameras positioned at different angles to triangulate depth information. The researchers' method requires one camera, and does not use a lot of compute power, said Guan. "Structured light imaging has several benefits [including] lower computational cost to extract the depth video from the raw recorded data," said Guan.

The light patterns are comparable to sunlight coming through Venetian blinds and striping objects in a room, said Guan. "When viewed from an angle, the stripes are crooked due to the objects, and this distortion can be used to calculate the three-dimensional shapes" of the objects, he said.

The problem with using just one set of stripes is that when an object has an edge, the computer will lose track of which stripe is which. The key to the scheme is that the researchers use several different patterns of light and triangulate to gain full three-dimensional information. "Multiple patterns are... required to achieve non-ambiguity and good depth resolution," said Guan.

The researchers' device projects a composite image, separates out the individual patterns, and triangulates to determine the depth information just as if the patterns were projected and captured separately, said Guan. The setup captures depth information quickly — as fast as the camera image can be digitized, he said.

Previous structured light depth imagers have used multiple patterns, but had to process them one at a time. The researchers got around this problem by making each pattern sweep sideways at a different speed. The speeds are analogous to radio station channels, said Guan. "Each pattern has its own carrier frequency, or channel," he said. The camera uses the frequencies to separate and analyze the patterns simultaneously.



Source: University of Kentucky

The top images show four simultaneous scans of an object. The bottom image is the view constructed from the depth information collected by those scans.

There's a long list of possible applications, according to Guan. "We're going to investigate human-computer interaction and automated surveillance applications," he said. The camera could also be used in manufacturing to inspect objects from afar.

The researchers tested the light pattern method in a setup that allowed people to change viewpoints in a virtual reality environment by moving their hands backward and forward. They also used the scheme as part of a computer interface that allows people to issue commands by making the motions of pressing buttons.

The researchers are working on implementing the depth camera prototype into a head and hand tracker that will allow persons with disabilities to interact with computers, said Guan. "In this case, it is a primary goal for work to keep the price tag of the device under the $4,000 threshold" including the PC involved, he said.

Eventually the technology could find its way into consumer video cameras, said Guan. In the movie Minority Report, Tom Cruise's character watches a home video of his son on a holographic display where a full, three-dimensional reconstruction of the child walks out of the background. "We hope to build a camera that would be the recording device for that scene," he said.

The researchers are working on combining the depth capture information with regular video to make a true three-dimensional camera, said Guan. The goal is to "move the structured-light source and the camera into the near infrared range, and then to couple a standard [color video] camera such that the resulting signal will be an RGB-plus-depth video signal," he said.

Such a camera could also be used instead of the many cameras required today to obtain three-dimensional special effects like those seen in the movie Matrix, said Guan. "Instead of using hundreds of single image cameras to obtain 3D special effects... only three or four three-dimensional video cameras would be necessary," he said. And "rather than a limited special effect, a full surround 3D video format could be made that could be viewed with [the] orientation controlled by the viewer," he said.

What the researchers have accomplished so far constitutes a good approach to capture a rough depth map of a scene, said A. Ardeshir Goshtasby, a professor of science and engineering at Wright State University. "This is useful in robot navigation where [an] approximate depth map is sufficient," he said.

A practical three-dimensional video camera is possible within two years, said Guan.

Guan's research colleagues were Lawrence G. Hassebrook and Daniel Lau. The work appeared in the March 10, 2003 issue of *Optics Express*. The research was funded by NASA.

Timeline: < 2 years
Funding: Government
TRN Categories: Computer Vision and Image Processing; Human-Computer Interaction
Story Type: News
Related Elements: Technical paper, "Composite Structured Light Pattern for Three-imensional Video," *Optics Express*, March 10, 2003

TRN

Shaky Chip Makes For Bug-Eyed Bots

By Chhavi Sachdev , Technology Research News
April 11, 2001

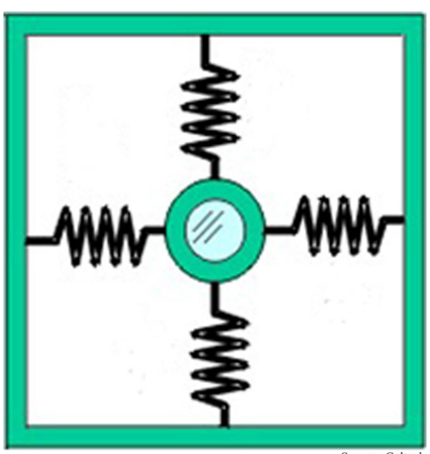
Technology often borrows from nature. Robots, for example, are often designed to imitate humans. One group of robot vision researchers, however, is borrowing from a much less expected source: a creature with eight legs, as many eyes and the potential to frighten many a human.

Conventionally, the more photoreceptors a vision system has, the higher the quality of its vision. The jumping spider, however, does things differently, and researchers at the California Institute of Technology are following along with an eye toward improving robot vision.

The research counters conventional wisdom by enabling high resolution robot vision while using fewer photoreceptors. The principle underlying the system is simple: the sensor moves like the retinas of the jumping spider. The research could lead to visual sensors that are smaller, use less power, and require less computer processing than traditional robot vision systems.

The jumping spider is noted for its unusually good sight, making it the ideal model for robotic visual sensors, according to the researchers.

The spider sees so well by rotating its retinas in a linear orbit — like the minute hand of a wristwatch ticking clockwise - and, at the same time, sweeping them back and forth like a pendulum. This allows it to see much better than other invertebrates and even rival human visual acuity, though it has only about 800 photoreceptors in each of its two scanning retinae. Compare this with the human eye, which has 137 million photoreceptors, and standard digital cameras, which use up to a million receptors.



Source: Caltech

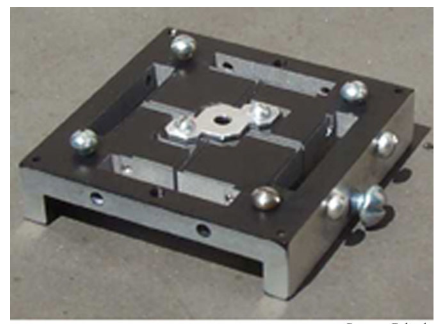
This diagram depicts a vision sensor for robots. The sensor uses springs to vibrate a lens in order to increase its resolution.

The researchers' vision system is based on a chip containing 1,024 photoreceptors, or pixels, arranged in a 32 x 32 array and spaced 68.5 microns apart. Each receptor is also 68.5 microns wide. The chip measures 10 square millimeters, or a little over 3 millimeters on a side.

Following the spider's lead, the researchers devised two different systems. In the first design, the photoreceptors image a circular scanning path by spinning a tilted mirror in front of the focusing lens. The output of this imaging "is extremely easily measurable and regular," said Ania Mitros, a graduate student at Caltech. The system uses 60 to 100 milliwatts to power the scanning motion, making it suitable for mid-sized robots, according to the researchers.

The second design uses even less power by harnessing the motion of the robot itself to vibrate springs that cause a sideways and backward movement of the lens while keeping the chip a fixed distance away. The continuous vibrations allow the pixels to measure the distribution of light intensity at various locations. The entire system measures just over a square inch.

"[It] is appropriate for platforms with a lot of inherent high frequency vibrations such as helicopters and where power is scarce such as …flying robots," said Mitros.



Source: Caltech

The springs are not visible in this photograph of a vision sensor, which measures slightly more than one inch square. The lense is under the light-colored piece of metal in the center of the device.

Because both systems remain in constant motion, they scan objects in a path rather than by measuring the light distribution at fixed points like other vision systems, said Mitros. This means the pixels are tracking changes in light intensity over time, which allows the system to process the signal from each pixel independently.

Vision systems collect huge amounts of data, much of it redundant. Having fewer photoreceptors leaves more room for processing the information on the chip, which cuts down the amount of pixel data before it has to be transmitted.

Processing each photoreceptor's output independently also helps eliminate fixed-pattern noise, or interference from mismatches in processing circuitry and photoreceptors.

The bad news is that the method isn't infallible. Each moving pixel in this system can see a line as well as 49 standard static pixels can. "However, since the scan path isn't necessarily going to cover every single point in space, you might still miss a dot of the same diameter as a detectable wire," said Mitros.

Slowing the circular scanning motion by a factor of two, will allow the sensor to detect a feature that's twice as narrow, but there is a tradeoff. "If something moves within the image before we finish scanning our local area, we'll get blurring," she said.

The vibrating system doesn't have this problem, but because its motion is irregular, it is not guaranteed to cover every point in space.

The researchers have designed a second version of the chip that they plan to test in a robot by this summer, Mitros said. The researchers' visual sensor design could eventually be used in any robot that moves and gathers information, be it in seek and find missions or in explorations of another planet's surface.

"Researchers working on [small flying] vehicles are interested since small, very low-power sensors are hard to come by," said Mitros.

The ultimate goal of implementing real-time robotic navigation tasks and feature detection using this scheme could take 10 years, however. "Really navigating well in a natural environment requires solving multiple tasks: route planning, object identification, [and] obstacle avoidance," said Mitros.

Mitros's research colleagues were Oliver Landolt and Christof Koch. They presented the research at the Conference on Advanced Research in Very Large Scale Integration (VLSI) in Salt Lake City, Utah, in March 2001. The research was funded by the Office of Naval Research (ONR), the Defense Advanced Research Projects Agency (DARPA), and the Center for Neuromorphic Systems Engineering, as part of the National Science Foundation (NSF) Engineering Research Center Program.

Timeline: 1 year
Funding: Government
TRN Categories: Computer Vision and Image Processing; Robotics
Story Type: News
Related Elements: Technical paper, "Visual Sensor with Resolution Enhancement by Mechanical Vibrations", Proceedings, Conference on Advanced Research in Very Large Scale Integration (VLSI) in Salt Lake City, Utah, March 2001: www.klab.caltech.edu/~ania/research/LandoltMitrosKochARVLSI01.pdf

Navigation

Robot Guided by Its Voice

By Kimberly Patch, Technology Research News
April 7/14, 2004

Two years ago, when University of Toronto researcher Parham Aarabi tried to use one of the University's Artificial Perception Lab robots to give tours to the several dozen high school students, corporate personnel, professors and journalists who traipse through the facility every year, he ran into implementation problems.

"I thought that using one of our robots for a lab tour guide would be good idea," said Aarabi. The robot has a motorized base and speakers that play pre-recorded phrases at appropriate locations. "The problem was that this robot... was rather inaccurate in its motions," said Aarabi.

The problem spurred Aarabi and his students to devise a relatively simple way for the robots to navigate more accurately. Instead of mimicking human sight-based methods, the researchers turned to sound. "Since my students and I had been working on microphone-array-based sound localization, the idea just came to us to combine robot navigation and sound source localization."

Source: University of Toronto

This museum guide robot navigates by pin-pointing the sound of its own voice using a series of microphones placed around the room.

As the lab's revamped robot tour guide explains the importance of various stations on a lab tour, every phrase it says is recorded by 24 microphones embedded in the wall, said Aarabi. "After some signal processing, the microphone array determines what location the sound came from." The system requires about two seconds of sound to get enough information to peg the robot's location.

The robot also has whisker-like touch sensors that determine when an object is in its path. When this happens it backs up, reorients itself and plots a new course around the obstacle. The obstacle's location is stored in memory so the robot can avoid it in the future.

Designing the system as a whole and integrating all the sub-components was the hard part, he said. This included crunching the data from the 24 microphones to compute the robot's location in real-time and coordinating the information with the robot's control and navigation systems. Given the location of the robot and its destination, it was a fairly simple task for a computer to compute the best route, he said.

The navigation system is accurate to 7 centimeters. "Ours is not the most accurate method, however it is perhaps the simplest and cheapest approach," said Aarabi.

In its sub-functional form, the robot seemed like a mechanical device or tool, but when the parts were all combined "it almost took on a new personality," said Aarabi. "I guess that's what happens when a 1.6 meter-tall object moves in a seemingly intelligent fashion around a room and makes interesting remarks," he said.

The next step is to make the robotic tour guide more intelligent, said Aarabi. "In other words, enable it to ask, understand, and answer the questions that are asked of it," he said.

This is no small task. "It requires robust speech recognition, natural language processing and understanding, followed by interpreting the question that was asked," said Aarabi.

The sound navigation system could be used in tour guide applications that don't require speech recognition and understanding with a year or two, said Aarabi. More elaborate systems that recognize speech are further off, he said.

The sound navigation system could eventually be used as a component of a multimodal navigation system that combines sound and cameras to provide very accurate navigation, according to Aarabi.

Aarabi's research colleagues were Qing Hua Wang and Teodor Ivanov. The work appeared in the November 14, 2003 issue of *Information Fusion*. The research was funded by the Natural Science and Engineering Research Council of Canada, the University of Toronto, the Canada Foundation for Innovation, and the Ontario Innovation Trust.

Timeline: > 2 years, 3 years
Funding: Government, University, Institute
TRN Categories: Robotics; Applied Technology
Story Type: News
Related Elements: Technical paper, "Acoustic Robot Navigation Using Distributed Microphone Arrays," *Information Fusion*, November 14, 2003

TRN

Decision-Making

Robot Automates Science

By Kimberly Patch, Technology Research News
January 28/February 4, 2004

What better entity to assign repetitive scientific tasks, like working out the function of specific genes, than a robot?

A group of researchers from from the University of Wales, Robert Gordon University in Scotland, and the University of Manchester in England have put together a robot scientist that can devise a theory, come up with experiments to test the theory, carry out the experiments, and interpret the results.

The researchers put the system through its paces testing yeast genes, and also had a control group of computer scientists and biologists perform the same task. "The robot performed as well as the best humans," said Ross King, a professor of computer science at the University of Wales.

The researchers also showed that the robot scientist's method of selecting experiments was both faster and cheaper than choosing the cheapest experiment or simply choosing experiments randomly, said King. The robot scientist was three times cheaper than choosing the cheapest experiment and 100 times cheaper than random selection, according to King.

The approach could make scientific research less expensive, and could be applied within a few years in areas where the level of laboratory automation is already high, like drug design, said King. Today's state-of-the-art drug design uses brute force automation.

The robot scientist consists of a computer running artificial intelligence software, a fluid-handling robot, and a plate reader that checks the experimental results for variables like color.

The software allows the system to "infer new scientific hypotheses and plan efficient experiments to test those hypotheses," said King. The robot conducts experiments by dispensing and mixing liquids, then measuring the growth of yeast using the plate reader, which feeds the results back into the system, he said. There is no human input in the design of experiments or interpretation of data, King added.

The researchers gave the robot the task of testing gene functions in Saccharomyces cerevisiae, also known as baker's yeast. "The robot scientist generates a set of hypotheses from what it knows about biochemistry and then plans an experiment that will eliminate as many hypotheses as possible as fast and as cheaply as possible," said King.

The robot scientist looks for the function of a given gene using knockout strains of yeast that have had one gene removed. Observing how yeast grows, or does not grow, on surfaces that contain specific chemicals gives the investigator clues about different possible functions for the gene, he said. "This is like trying to understand what the different components in a car do by removing them one by one."

The robot evaluates the results against the set of hypotheses, interprets the results to eliminate hypotheses that are inconsistent with the data, generates new hypotheses, and repeats the process, said King. This is the same type of cycle human scientists use to understand the world, he said.

This standard process is relatively tedious for humans to carry out, however. The functions of about 30 percent of the 6,000 genes contained in baker's yeast are still unknown, said King. "With many of these genes thought to be common to the human genome, they could prove to be medically important," he said.

The software challenges involved in constructing the robot scientist included encoding all the relevant background information in a form that the system could use, developing a way of inferring possible hypotheses, and developing a way of inferring efficient experiments, said King. The engineering challenge was to put everything together into a working system, he added.

The researchers have demonstrated the system as a proof of principal. The next step is to show that the system can discover the function of genes that are currently unknown, said King.

The researchers drew on a 30-year history of research in artificial intelligence to make the system, said King. "The application of artificial intelligence to science is known as the field of scientific discovery," King said. " I think the main step forward of our work is... connecting such programs to a physical robotic system."

The work is solid, and important, according to Pat Langley, director of the Institute for the Study of Learning and Expertise located at Stanford University. It differs from previous systems that use artificial intelligence to control robotic equipment because it takes advantage of background knowledge, is aimed at designing efficient experiments, and uses a closed experimental loop so that the results inform the next hypothesis.

The work is part of a branch of artificial intelligence dubbed active learning that develops algorithms that weigh the odds of hypotheses being correct and the costs of potential experiments to determine the optimal series of experiments to eliminate all but the correct hypothesis.

In general, techniques for cognitive science and artificial intelligence should be as applicable to modeling and replacing scientific discovery and experiment design as for more mundane tasks, said Langley. The researchers work is a step along these lines, he said.

The ideas have precedents, said Raul Valdes-Perez, president of Vivisimo, Inc. and an adjunct associate professor of computer science at Carnegie Mellon University. But "I would say that this is the first convincing demonstration of a link between completely automated physical experimentation and hypothesis generation and testing," he said.

The robot scientist could be ready for practical use in three to six years, according to King. The first practical use is likely to be making drug design more efficient, he said.

Ross's research colleagues were Kenneth E. Whelan, Ffion M. Jones and Philip G. K. Reiser of the University of Wales, Christopher H. Bryant of the Robert Gordon University in Scotland, Stephen H. Muggleton of Imperial College, London in England, Douglas B. Kell of The University of Manchester Institute of Science and Technology (UMIST) in England, and Steve Oliver of the University of Manchester in England. The work appeared in the January 15, 2004 issue of *Nature*. The research was funded by the UK Biotechnology and Biological Sciences Research Council, and the UK Engineering and Physical Sciences Research Council.

Timeline: 3-6 years
Funding: Government
TRN Categories: Artificial Intelligence; Robotics; Applied Technology
Story Type: News
Related Elements: Technical paper, "Functional Genomics Hypothesis Generation and Experimentation by a Robot Scientist," *Nature*, January 15, 2004

TRN

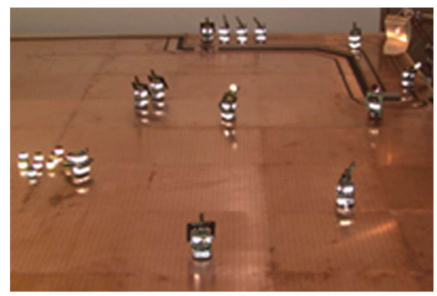
Ants Solve Tough Problems

By Kimberly Patch, Technology Research News
September 27, 2000

For well over a decade, scientists have been watching the way insects organize themselves with an eye toward making human tasks more efficient, and they're still learning.

A group of Swiss and U.S. researchers, for instance, have produced little robots that organize themselves with social behavior patterns derived from ants. Other researchers are looking to ant colonys to increase efficiency in truck routes, network routing, and distributed decision-making.

The robotics researchers are using ant algorithms to tackle one of the stickiest problems of their field: making machines that can deal with the unpredictable. Those researchers programmed a swarm of small robots with algorithms modeled after the decentralized control techniques of an ant colony.



Source: University of Georgia
A colony of ant-like robots forages for pucks, which represent food. The robots carry the pucks from a source on the left to their "nest" at the upper right.

The robots, like ants, recruited other robots when they discovered large piles of the "food" pucks they were programmed to collect, and this behavior increased their foraging efficiency. "Simple ant-based algorithms can be used efficiently to make a group of robots work together," said Laurent Keller, a professor of evolutionary ecology at the University of Georgia, Athens.

The experiment also showed a more surprising result. As the number of robots involved in a task passed a certain size, the robots became less efficient. According to Keller, the relationship between group size and efficiency was similar to that documented in social insects. "There is an optimal group size, just as in ants," he said.

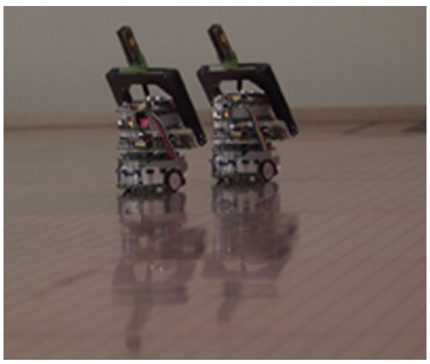
Source: University of Georgia
Two robots carry food pucks to the nest.

Keller's next step is to coax antlike division of labor out of the robots, he said. Eventually, ant algorithms could be used to help robots work without oversight in areas where humans cannot go, he said.

Meanwhile, another researcher is applying ant colony experience in discovering the shortest path to a food source to truck and network routing.

Ants are efficient as a group because they lay and follow chemical trails of pheromone, said Eric Bonabeau, CEO of Eurobios. "The first ants returning to the nest from a food source are those that take the shorter path twice — from the nest to the source and back," he said. The ant's nestmates find the shortest trail by following the strongest chemical path.

Bonabeau is using this process to tackle problems that have so many variables they bog down today's computers. One example is the classic problem of finding the most efficient route for a traveling salesman who must visit several cities. It may sound easy, but for only 15 cities, there are billions of route possibilities.



Source: University of Georgia

When a robot finds a source of food pucks, it recruits other robots to help carry the pucks to the nest. Here one robot leads another to a food source.

One problem with ants is they won't select a shorter path that is discovered later because the original, longer branches are already marked with pheromone, said Bonabeau. Ant algorithms can overcome this problem by allowing the computer equivalent of pheromone to decay more quickly than the ant pheromone does, said Bonabeau. "When the pheromone evaporates sufficiently quickly, it is more difficult to maintain a stable longer path. The shorter branch can be selected even if presented after a longer branch."

This turns out to be a much more efficient way to tackle route problems then checking all the possibilities. In addition to finding a good route, the algorithms also provide a pool of alternate solutions, which can be tapped when conditions change, according to Bonabeau.

One of Bonabeau's real world applications is truck routing for a Swiss company. Bonabeau's company is a consulting firm that applies science like ant algorithms to business problems.

The route problem is "first expressed in mathematical form, often in terms of a graph with nodes and edges... the nodes would be cities and the edges the roads that connect the cities," said Bonabeau. "The artificial ants go from node to node, reinforcing some of the edges with virtual pheromone." Bonabeau is also applying the algorithms to networks in a similar way.

Bonabeau's work is "novel and demonstrates a portion of the capability of [ant] techniques. It shows they do have mathematically attractive optimization characteristics," said H. Van Parunak, chief scientist at the Environmental Research Institute of Michigan (ERIM), and another longtime ant algorithm researcher.

The work is also practically useful because there are "a large selection of commercial problems that... are complex," he added.

But the ants still have uncracked secrets.

While Bonabeau's practical applications take advantage of ant's abilities to efficiently solve problems that have many possible solutions, the problems are solved with static data. Ants, on the other hand, change their behavior in real-time.

Parunak is working on adding the real-time element to ant algorithms. This means gathering distributed information that is changing as you gather it, he said. He is also aiming to distribute the decision processes out to where the real-time information is, which is how the ants do it.

For instance, if you want to use real-time information to make the most informed sales decision involving three cities, you need information on the state of the world at the same moment in all three cities, said Parunak. If a single person is making a decision involving distributed information it is usually based on static, somewhat mismatched information like yesterday's sales figures in New York and today's sales figures in Chicago. But "the world was never in that state," he said.

With distributed decision-making, someone in New York would be "making a decision based on information in New York, ... not worrying about the information in Chicago," said Parunak. If you can do this, you can "change the weightings among different criteria dynamically as the system runs," he said.

This type of ant behavior is especially apt in situations that change very quickly, like Air Force maneuvers, Parunak said. "No plan survives contact with the enemy. [If] the planes take off, and something changes and the plan is now in the hopper ... everybody's got to figure out for themselves what's the right thing to do." Parunak's computer models show if planes act like a swarm of ants in finding their way through the enemy in these situations, they're more effective, he said.

Bonabeau's work has been funded by his three employers since 1990: France Telecom, the Santa Fe Institute and Eurobios. Parunak's work is funded by DARPA.

Keller's colleagues were Michael Krieger of the University of Lausanne in Switzerland and Jean-Bernard Billeter of the Swiss Federal Institute of Technology. Their work was funded by the Swiss government and the University of Lausanne in Switzerland. They published their work in the August 31, 2000 issue of *Nature*.

Timeline: Now
Funding: Corporate, Government
TRN Categories: Data Structures and Algorithms; Robotics
Story Type: News
Related Elements: Technical Paper "Ant-like Task Allocation and Recruitment in Cooperative Robots" in Nature, August 31,

2000; Technical Paper "Inspiration for Optimization from Social Insect Behavior" in Nature, July 6, 2000.

Coordination

Cooperative Robots Share the Load

By Chhavi Sachdev, Technology Research News
February 13, 2002

If two heads are better than one, then four arms are probably more useful than two. But as Laurel and Hardy repeatedly demonstrated, coordination can be an issue — especially if the task at hand entails carrying heavy equipment over uncharted terrain.

Coordinating robots is also tricky, but is potentially very useful. Networked robots could accomplish more than they could individually by coordinating their actions and by sharing sensors and computing power.

Researchers at NASA have demonstrated that a pair of networked rovers can work together to move large objects, drill holes and pitch tents in tight coordination. And they can carry out the tasks in an unstructured outdoor environment.

Source: NASA

These NASA robots combine their sensory data in order to carry out cooperative tasks, like carrying a metal beam, more efficiently.

The robots' capability for handling and transporting large objects could be used in space exploration, the military, and in manufacturing, said Paul Schenker, the supervisor of the Mechanical & Robotics Technologies Group at NASA's Jet Propulsion Laboratory.

Each robot is about 3 feet tall, 2 feet wide and 1 foot deep and weighs around 20 pounds. Each robot has four wheels and a 27-inch gripping arm with which it can lift, grasp, and move objects. It also carries instruments that measure the surrounding terrain and its position; these include visual, kinematics and acceleration sensors.

The robots' software maps the terrain they tread and guides their shared responses. The rovers avoid obstacles "by developing local visual three-dimensional terrain maps and cooperatively planning a drive-around… strategy, changing their formation and steering as needed," Schenker said.

The robots react in real time to their physical position and the weight of their payloads, he said. Sensors help them maintain an accurate estimate of their position and visually track objects.

The system's intelligence is evenly distributed between a pair of robots. Information about the terrain, their payload, positions and speeds is fused into a shared estimate, he said. Two robots can carry an 8-foot long beam for 50 meters without faltering because they are constantly aware of each other's state, said Schenker.

The actions are fully autonomous, he said. "Control is a true team decision process, mediated by various negotiation-decision strategies."

The underlying behavior-based control software is fairly general, said Schenker. "It can be extended to incorporate many robots, as well as readily augmented with new skills [and] behaviors," he said.

The results of this work are quite significant, said Reid Simmons, a senior research computer scientist at Carnegie Melon University's Robotics Institute. "The work has great potential for future multi-rover outposts."

"While others, including ourselves, have looked at close coordination between multiple robots in a distributed setting… this is the first such effort to operate in natural terrain," Simmons said. Operating the robots in a natural setting "adds complexities in terms of deciding what to do, and how to coordinate behavior to both achieve the task and avoid obstacles," he said. This makes it applicable for more than just space exploration, he said.

The researchers plan to further develop the robots' fused sensing, said Schenker. They also plan to increase the robots' cooperative control and task-planning functions, and evaluate them in realistic outdoor experimental settings, he said.

"We expect some of the related technologies, particularly the behavior-based functions for rough terrain navigation, to be used in the next 3 to 5 years," Schenker said. A robot outpost on Mars, for which the networked robot crews were developed, will take much longer to come to fruition, he said.

Schenker's research colleagues were Terry L. Huntsberger, Paolo Pirjanian, and Eric T. Baumgartner.

The research was funded by NASA.

Timeline: 3-5 years
Funding: Government
TRN Categories: Robotics; Human-Computer Interaction
Story Type: News
Related Elements: Technical paper, "Planetary Rover Developments Supporting Mars Science, Sample Return And Future Human-Robotic Colonization," published in the proceedings of the IEEE 10th International Conference on Advanced Robotics, Budapest, Hungary, August 22-25, 2001

Bots, Humans Play Together

By Eric Smalley and Kimberly Patch, Technology Research News
December 31, 2003/7, 2004

How do you get to know a robot?

Researchers from Carnegie Mellon University are betting that putting humans and robots on the same soccer team will encourage the kind of cooperation that leads to understanding.

The researchers have made a human-size version of their soccer-playing robots by basing the robots on Segway scooters, and they are working on a set of rules for Segway soccer, a game designed to be played by mixed teams of the robots and humans riding Segways.

The project is designed to allow researchers to look at human-robot interactions in which humans and robots are on nearly equal footing, said Manuela Veloso, a professor of computer science at Carnegie Mellon University. The two types of players will have nearly the same acceleration, the same top speed, the same turning abilities, and will use the same ball manipulation device, she said.

The setup makes it possible to explore questions like how and when humans and robot should communicate, and how they should divide a common task, said Veloso. "There are many really interesting challenges here that we now have the opportunity of investigating," she said.

Source: Carnegie Mellon University

A Segway-based robot equipped with a paddle is poised to kick a soccer ball as a person on a Segway scooter tries to intercept it.

This promises to translate to any application that requires multiple robots to work with people in real-time, said Veloso. Examples are autonomous robot vehicles sharing the roadway with human-driven vehicles, robot building construction crews, search and rescue operations, and space exploration. These tasks all require real-time decision-making and action, she said.

The preliminary set of Segway soccer rules calls for human players to carry devices that allow them to communicate with the robotic players. The players will use a size five soccer ball, but for safety's sake, dribbling is not allowed, only passing. And to encourage human-robot interaction, the sequence of passes leading to a goal will include at least one robot and one human. The game will be played on a soccer field proportional to a standard soccer field, but scaled depending on the number of players.

The Segway base's dynamic balancing ability enables human-size robots because it allows a relatively small base to support a human height. "It's dynamic balancing also creates interesting effects," said Veloso. "We need to worry about obstacles not just from the viewpoint of hitting them, but also because the robot might fall over," she said.

At the same time, dynamic balancing creates compliance — where you can push the robot and it backs away smoothly, Veloso said.

The researchers designed a pneumatic ball-handling mechanism that enables the robots to kick the ball, and a second mechanism that prevents the ball from going under the Segway base.

The human-size soccer robot also has a vision camera and algorithms that allow it to to recognize and track the soccer ball in the variable light conditions of the outdoors, said Veloso. The robot contains pair of laptop computers, one to processes images from the camera, and another to run algorithms that allow it to select an action.

The researchers have also developed a computer infrastructure, including a graphical user interface, teleoperation programs, and logging programs, that allows them to quickly develop and evaluate robot control algorithms. "The GUI lets us see what is going on inside the robot's head, teleoperation allows us to manually drive the robot around, [and] logging allows us to record sensory data and play it back at a later time," said Veloso.

And to teach the robots to play soccer, the researchers developed skill-learning techniques that involve teleoperating the robot through a sequence of motions, said Veloso. "We record these motions and play them back on command," she said. "We can record the complex motions involved with, say, kicking a ball, and then reproduce them when the robot needs to kick." This replaces the need to work out a complex program for kicking, she added.

The Segway soccer robot is fully autonomous, said Veloso. "It can reliably follow a ball and effectively kick it," she said.

The researchers are working on finalizing the robot structure and the Segway soccer rules, said Veloso.

On the robot side, the researchers are working on transferring the soccer-playing software designed for smaller robots to the Segway, improving the robot's ability to avoid obstacles using vision as the primary sensor, and adding the technology that will allow humans to send commands or messages to the robots, said Veloso. The robot already has the capacity to speak, she added.

Once this is done, the researchers will begin studying human-robot interactions by observing how they interact in playing Segway soccer.

Robots designed for specific applications could become practical in 5 to 10 years. Robots that interact with other robots and humans in general applications will take longer — at least 20 years, said Veloso.

The project is one of a dozen projects at universities and government labs around the country that involve building robots on Segway bases. The projects were initiated by the

Defense Advanced Research Projects Agency (DARPA) Mobile Autonomous Robot Software (MARS) program.

The research was funded by the Defense Advanced Research Projects Agency. Veloso's research colleague was Bret Browning.

Timeline: 5-10 years, 20 years
Funding: Government
TRN Categories: Robotics; Engineering
Story Type: News
Related Elements: Segway soccer robot web site: www-2.cs.cmu.edu/~robosoccer/segway

Human-Robot Interaction

Interactive Robot Has Character

By Eric Smalley and Susanna Space, Technology Research News
March 6, 2002

Combine some of the most advanced human-computer interaction technology with one of the oldest forms of entertainment — puppetry — and you get Horatio Beardsley.

Doc Beardsley is an animatronic robot, a descendant of the mechanical humans and beasts that rang bells and performed other actions as parts of the clocks of medieval European cathedrals. Modern science, however, has carried Doc far beyond these ancient automata, endowing him with the ability to see, understand spoken words and carry on a conversation.

Researchers at Carnegie Mellon University made the amusing, forgetful inventor as a literal embodiment of a computer interface. Doc performs for audiences, answering questions about himself. He claims to have been born on a mountaintop in Austria to a family of goatherds, and to have invented endless bread, the milkbed, the antisnooze and the foon.

In addition to paving the way for a future generation of theme park animatronic characters, the technology could lead to embodied personal digital assistants with personalities, interactive electronic pets, animated historical museum figures, and robotic waiters and salespeople, said Ron Weaver, a graduate student at Carnegie Mellon.

Several layers of software drive Doc's apparent wit. Synthetic interview software, which includes speech recognition abilities, allows Doc to react to spoken questions. The technology, developed at Carnegie Mellon for use with video characters, gives a character sets of lines to deliver on given topics. This allows Doc to give appropriate answers to questions that match an anticipated query closely enough, said Weaver.

If the question hasn't been anticipated, another layer of software takes over. A discussion engine tracks the questions and answers during a conversation and allows Doc to make relevant comments by keying off individual words even if he doesn't understand a specific question, said Weaver. And if that doesn't work, the discussion engine tosses the conversation back to the questioner, he said.

"The discussion engine will first try to deliver a comment that is still relevant based on whatever individual keywords can be found in the text," said Weaver. "Failing that, the character gives a random comment that either pretends to reflect what is being discussed to try to keep [the conversation] going, or transfers the onus of the conversation back to the guest."

The researchers made Doc forgetful to help keep his lapses from breaking the illusion of a realistic personality.

Here's an actual exchange:

Questioner: "How are you feeling today?"

Doc: (pause) "My— my dog just died. No, I'm just kidding. He just got run over. He's still alive. Well, it's a she really. I just refer to her as a boy to bust her chops, keep her honest, you know?"

Questioner: "What's your best invention?"

Doc: "Well, you know, there was this one invention I made accidentally while working on genetic recombination. I crossed a spoon with a fork and thus created the foon. It was used either as a spoon or a fork."

Source: Carnegie Mellon University

Doc Beardsley's animatronic body gives him mobility and facial expressions. Unlike ordinary animatronic figures, however, Doc can see, hear and hold up his end of a conversation.

Microphones and cameras that track the sounds and movements of an audience provide Doc's audiovisual perception, said Todd Camill, a research engineer at Carnegie Mellon University's Robotics Institute.

"Microphones listen for sounds made by people in the room, and a camera subsystem tracks the movement of people by finding areas of skin tone in the room. The audio and vision systems generate position data that tell Doc where to turn his head."

One aspect of making Doc Beardsley a believable character is keeping the technology in a supporting role, according to Tim Eck, another Carnegie Mellon graduate student. "Character and story are the most important aspects to creating believable, entertaining characters," he said. "We are striving to provide the illusion of life, to create an entertaining experience, which is an important distinction. We are not trying to create artificially intelligent agents. We are creating the illusion of intelligence with time-tested show business techniques: drama, comedy, timing and the climactic story arc."

As with many creative endeavors, serendipity plays an important role. "From time to time, we find ourselves caught off guard by conversations that seem to make sense in ways we did not intend," said Camill. "For example we've recently heard this exchange:

Guest: 'Doc, why are you wearing a Carnegie Mellon University sweatshirt?'

Doc: 'I've spent time at many universities. You'd be surprised at the things they throw away.'"

In addition to using traditional storytelling and theatrical techniques, the researchers are studying the human side of human-computer interaction. "Since our goal is the illusion of human intelligence or intent in the service of a story, a large part of our results concern the human audience rather than the robot," said Camill. "We are exploring the social dynamics between human and machine by exploiting the tendency of people to project human qualities on the objects around them."

From the entertainment perspective, the ultimate goal is creating synthetic characters that seem to possess dramatic human qualities, like a sense of humor, comic timing, personal motivations and improvisation, said Camill. "When an audience can get so engrossed in interacting with Doc's dialogue and story that the technology is completely forgotten, then we know we have accomplished our goal," he said.

The next steps in the project are improving the character by adding skin and a costume, building a set and props, creating a show, building puppeteering controls for the props, and writing software for producing other shows, said Camill.

The technology is not yet ready for the entertainment industry, said Eck. "The main reason [is] speech recognition technology. We believe once the overall accuracy of speaker-independent speech recognition is 80 percent or higher, applications such as ours will be seen in the entertainment industry. This will be approximately 5 to 8 years from now," he said.

The research is funded by the Carnegie Mellon University.

Timeline:5-8 years
Funding:University
TRN Categories: Robotics; Artificial Intelligence
Story Type: News
Related Elements: Project website: micheaux.etc.cmu.edu/~iai/web/newIAI/doc.html

TRN

Manners Matter for the Circuit-Minded

By Ted Smalley Bowen, Technology Research News
April 25, 2001

In his dystopian futuristic comedy, "Sleeper", Woody Allen's twentieth-century time traveler, on the lam as a domestic robot, is revealed when, among other breaches in automaton etiquette, he betrays a fondness for his owner's euphoriant orb.

While sophisticated androids are still the stuff of science fiction, robotics technology is creeping closer to the point when mobile robots will be commonly employed for personal use.

Anticipating frequent human-robot interaction, researchers are trying to get a sense of how people will be affected by the activities of their mechanized assistants. Such observations could lead to the design of well-behaved, and thus more effective, robots.

To this end, University of Kansas researchers put robots through their paces in the presence of human subjects and gauged the humans' reactions.

Among the lessons they learned: personal robot etiquette frowns on rushing headlong at people. This may come as no surprise, especially in the case of large robots, but relatively little quantitative research has been done on the psychological responses mobile robots elicit in humans, according to Arvin Agah, an assistant professor of electrical engineering and computer science at the University of Kansas.

Working with a commercially available mobile robot configured in two basic body types, the researchers recorded the reactions of forty people as robots approached and went around them, and when the robots simply moved about in their presence. The robots, which were based on the Nomadic Scout II made by Nomadic Technologies Inc., moved on two wheels and a caster.

The small robot body type was 35 centimeters high and 41 centimeters in diameter, or about the size and shape of a wide mop bucket. To make the larger body type, the researchers topped the small version with a rudimentary humanoid form to give it a height of 170 centimeters, or about five-and-a-half feet.

To determine the most acceptable ways robots might approach humans, the researchers guided robots of each size toward the human subjects in several ways.

In a direct approach, a robot went straight toward a human at the speed of 10 inches per second or at a faster clip of 40 inches per second.

In an avoidance mode, a robot moved around the subjects either by stopping to change direction or by making a continuous turn. The avoidance mode speed was 10 inches per second, but the evasive moves were made at a slightly faster 15 inches per second.

The robots were also set to work moving around the space while not interacting with the human subject. This involved both random movement and a more methodical sweep of the floor space.

The researchers carried out the experiments in the relatively close quarters of a lab room measuring about nine-by-fifteen feet. The subjects recorded their responses in a survey, rating them on a one-to-five numerical scale, with one representing very uncomfortable and five very comfortable.

In general, the humans liked the small robot better than the larger, humanoid version, said John Travis Butler, a software engineer at Lockheed Martin who participated in the investigation when he was a University of Kansas graduate student. "The smaller robot body was preferred in cases where the robot was moving fast or close to the subject due to the intimidation factor of the more massive-bodied robot," he said.

Source: University of Kansas

The top picture shows a small robot. The bottom picture shows the robot modified to be about the size of a human. Human subjects said they were more comfortable with the smaller robot, and more comfortable when it did not approach directly or make sudden moves.

In the direct approach experiments, the humans were generally comfortable with the slower approach, and were not at ease with the fast approach.

The avoidance mode was met with general approval, with the most positive reception given to the nonstop pass-by performed by the robot in its smaller incarnation.

While generally at ease with both types of non-interactive behaviors, the subjects were slightly less comfortable with the structured movements, which involved frequent and slightly faster turning.

Some of the behavioral concepts gleaned from such experiments are already being used in experimental designs, said Agah. "In research laboratories, the behavioral research is starting to be incorporated into the design of personal robots. In the industry, mostly entertainment/companion/pet robots, this will be happening in the next five years," he said.

While the behavior studies could inform the design of robots for both workplace and home settings, the requirements for those venues will likely differ, said Butler. "I would expect a work environment to be more structured and easier for a robot to operate in. [The] home would be a more dynamic environment," he said.

Workplaces will also be much more concerned with the amount of work done per dollar spent on the robot and less concerned about the attractiveness or noise of the robot, he said. "A robot working in someone's home will have to be something you can tolerate looking at every day. This will be something that the user will have to live with much like a pet. The expectations will be much higher," he said.

The University of Kansas research largely confirms similar studies of human reactions to robot actions, said Dieter Fox, assistant professor of computer science and engineering at the University of Washington. "This is an interesting article on design issues involved in the development of human-friendly service robots. Our experience [also] suggests that high acceleration is the major factor that makes people uncomfortable when being approached by mobile robots," said Fox.

However, Fox's own research shows one difference in human acceptance of robots. "In slight contrast to the results presented in this article, we had good experience with taller robots carrying human features," he said.

The next step in this type of research, said Butler, is evaluating more complex human-robot interactions by having robots perform more varied tasks with human subjects. "More interaction would give a better understanding of how people and robots will fit in the same environment," he said.

University of Kansas researchers are working on extending the work using robots that interact with people by responding to verbal and visual commands such as 'put the green one over there,' said Agah. "This requires dealing with ambiguity resolution, a concept that necessitated our multidisciplinary team of researchers including faculty from departments of electrical engineering and computer science, psychology, and linguistics," he said.

Additional work might include more detailed evaluations of human subject's behavior when they share space with mobile robots, said Butler. "Monitoring subjects as they perform normal daily activities while in the presence of an active robot would provide very interesting results," he said.

The researchers described their experiments in the March, 2001 issue of the journal *Personal Robotics*. The work was funded by the University of Kansas department of electrical engineering and computer science.

Timeline: 5 years
Funding: University
TRN Categories: Robotics; Computers and Society
Story Type: News

Related Elements: Technical paper psychological effects of behavior patterns of a mobile personal robot," *Personal Robotics*, March, 2001

Software Eases Remote Robot Control

By Chhavi Sachdev , Technology Research News
August 22/29, 2001

Remember when every kid had a remote control car, and sometimes parents did, too? Running around the house chasing a tiny car and jamming the joystick controls was a part of growing up. It seems that technology has grown up as well.

A team of researchers at Carnegie Mellon University and the Swiss Federal Institute of Technology at Lausanne has developed software that allows people to control the movement of a robot by using a computer or Personal Digital Assistant (PDA) and the Internet. The set up allows for remote control of a robot from anywhere in the world.

It's not just a game, though. "Our work is inspired by a wide range of remote vehicle applications, particularly military reconnaissance and planetary exploration," said Terrence Fong, a research assistant at the Robotics Institute at Carnegie Mellon University. The tools enable a user to understand the remote environment and control the remote vehicle better, Fong said.

Source: Carnegie Mellon University

This shows a person using a PDA to remotely control the movements of a robot.

Traditionally, even experts have found it difficult to remotely drive robots. The teleoperation tools make driving mobile robots easier because the user and the remote vehicle share control, said Fong. "Our work is centered on a concept called collaborative control, in which the human and the robot engage in dialogue," said Fong.

Operating remote vehicles using these techniques requires no special training, he said.

The human and the remote robot exchange questions and information, so the robot can decide how to use human advice, following it when it is forthcoming and relevant, and modifying it when the advice is unsafe or inappropriate, he said.

They aren't talking about a sentient HAL-esque being; the robot still follows a higher-level strategy set by the human. Still, the robot has more freedom in execution, which makes it able to function even when the human operator is unavailable or distracted, according to Fong. This makes the system more dependable, he said.

Source: Carnegie Mellon University

In the image manager mode of thePDA remote robot software, thelong horizontal line shows the horizon and shorter lines show the width of the robot at various positions in the field of view. A user can guide the robot by clicking waypoints on the schematic control area at the lower left of the PDA screen.

The PC version of the teleoperation system is dubbed WebDriver and the PDA version, PdaDriver. Both versions are designed to minimize network bandwidth usage. The systems function "even with low-bandwidth, high-delay networks," said Fong. Both interfaces combine several types of sensory input to give the human operator a composite picture of the robot's environment.

The system's input devices, which include a laser scanner, monochrome video camera, stereovision sensor, ultrasonic sonar, and an odometer, complement each other. For example, if the robot is standing directly in front of a smooth, untextured wall with a large plant close by, each sensor will miss something from the scene. With the sonar detecting the plant, the laser scanner following the wall, and stereo vision finding the wall's edge, the sensors take in the whole scene.

The Web version is a Java applet that allows the user to see the status of all five sensors and give the robot specific commands in several different ways. Instead of live video, the image server senses images only when something significant happens, such as if an obstacle appears, said Fong.

It has two primary modes: dynamic map, which shows radar and sonar inputs, and an image manager, which displays and stores data from the pan/tilt camera mounted on the front of the robot. Both modes allow a user to send commands, receive feedback and control the robot's camera. In image manager mode, the user drives the robot by clicking a series of waypoints and then pressing Go.

A user can also control the robot manually by telling it to, for instance, move forward 5 meters or turn right at 10 degrees per second. The user can do this in situations in which waypoint driving does not work, said Fong. The Web application also supports touchscreen controls, which could allow people to remotely control robots from devices in kiosks, Fong said.

The PDA version has four control modes: command, sensors, video, and map. In command mode a user controls relative position and motion of the robot by clicking on the display's vertical or horizontal axis. In sensors mode, the user can directly control the robot's on-board sensors to pan, tilt, and zoom the robot's camera, enable and disable sonars, and activate motion detection triggers, according to Fong.

Video mode displays images from a robot-mounted camera and map mode displays a sonar map from both robot and global frames of reference. The video and map modes also allow a user to control the robot's movement using waypoint clicking.

PdaDriver is an improved version of WebDriver, said Fong. "PdaDriver allows the user to specify a path... PdaDriver also supports collaborative control, so that the robot can ask questions of the human, [such as,] 'I seem to be stuck, can you help?'" said Fong.

The researchers are also working on a remote driving system, GestureDriver, which can be used without keyboard or joystick-based interfaces, said Fong. Putting the vision system on the robot allows a user to have a direct visual interaction with the robot, controlling it by hand gestures such as pointing an arm to where the robot should go, he said.

"Hand motions are converted to remote driving commands," said Fong. A computer vision system tracks the gestures and classifies them using a geometric model that maps the gestures to specific motion commands for the robot, according to Fong.

The researchers concede, however, that visual gestures are not the easiest way to command the robots. Testers reported that it is fatiguing, according to Fong.

They have also been working on a "drive-by-feel interface," called HapticDriver, which is hand controlled, said Fong. In this system, a "haptic device and robot sensors allow a user to feel the environment, thus avoiding collisions and enabling precision driving" and movements such as docking, he said.

The systems could eventually be used by geologists and astronomers to explore and retrieve samples from remote locations on earth and other planets, Fong said.

"The sensor fusion part is the most sophisticated and interesting," piece of the research, said Paul Backes, Technical Group leader at NASA's Jet Propulsion Laboratory. "The paper is a worthwhile collection of the concepts …each of the concepts they discuss seem realistic and valid for some applications," he added.

Fong's colleagues were Sébastien Grange and Charles Baur of the Swiss Federal Institute of Technology at Laussane, and Charles Thorpe at Carnegie Mellon University. They published the research in the July 2001 issue of Autonomous Robots. The research was funded by the Defense Advanced Research Projects Agency (DARPA), the National Science Foundation (NSF), and Science Applications International Corporation (SAIC, Inc.)

Timeline: 2-3 years
Funding: Corporate; Government
TRN Categories: Robotics; Human-Computer Interaction
Story Type: News
Related Elements: Technical paper, "Advanced Interfaces for Vehicle Teleoperation: Collaborative Control, Sensor Fusion Displays, And Remote Driving Tools," *Autonomous Robots*, July 2001 imtsg7.epfl.ch/projects/ati

Microrobots

Tiny Treads Move Miniature Robots

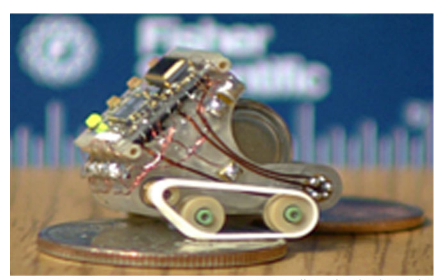
By Ted Smalley Bowen, Technology Research News
February 7, 2001

Mobility, or the problem of how to achieve it, presents robot designers with a large obstacle. To get around it, researchers at Sandia National Laboratories have switched from wheels to tank-like treads to propel their smallest robots.

The treads could make the researchers' miniaturization efforts pay off by allowing the tiny robots to traverse such difficult terrain as carpet.

The robots weigh less than an ounce and are equipped with an 8-kilobyte memory module, a temperature sensor, three watch batteries, and a pair of actuators.

"They're nine tenths of an inch long, seven tenths of an inch high and a half an inch wide, and they've got kind of a triangular profile," said Doug Adkins, a mechanical engineer at Sandia. The tiny robots travel about six inches per minute, though some have reached speeds of 10 inches per minute, he said. They can travel about 90 inches on one charge.



Source: Sandia National Laboratories

This microrobot is parked on a quarter. The robot's treads help it traverse rough terrain like carpet.

The robots are designed to work in hazardous and hard-to-reach settings, like narrow pipes. They could also be used for hazardous waste monitoring and clean-up, and surveillance in volatile situations like hostage rescue missions. The researchers have plans to add a camera, microphone, and chemical sensor to the little robots.

The work builds on the Labs' Mini Autonomous Robot Vehicle (MARV) project, which produced a slightly larger wheeled robot equipped with mostly off-the-shelf components. Adkins and Sandia materials scientist Ed Heller took the MARV concept a step further by shrinking the robots a little more.

The smaller robots are made from widely available un-packaged electronics parts and a form-fitted body that contains cavities for the components. The robot bodies are built using stereolithography, a rapid prototyping technique that uses a laser to harden successive layers of a liquid polymer.

The researchers' next reduction in scale is contingent on finding smaller batteries or using alternate power sources, said Adkins. The batteries account for half of the robot's 7.2-gram weight and one quarter of its volume.

"They won't get any smaller until we get a better battery," he said. "We would like to... build the battery around the robot, rather than... build the robot around the battery," he said.

Powering the robots using solar panels present a size problem, although a small collector could enable the robot to move in spurts, with pauses for re-charging, he said. "To drive these things with today's solar cells, I think we'd need like 30 square centimeters," he said.

Another alternative or supplement to batteries could come from harvesting ambient energy, Adkins said. "There's all sorts of little sources in your room, around outlets and everything else, that give off little [electromagnetic fields]," he said.

The researchers also plan to encase the robots' components to make them more durable and resistant to the elements, Adkins said. "Right now the microprocessor [platforms] are kind of exposed, so we're just going to pod [them over] once we are finished testing them out," he said.

They also plan to add infrared or radio communications to allow the robots to communicate with each other and with their human operators, said Adkins. The MARV robot design used a centrally-controlled communications system that controlled the units via a base station.

"I think the tank treads are quite a useful innovation, although ultimately, legs would give better terrain capability at this small scale," said Ronald Fearing, professor of electrical engineering and computer science at UC Berkeley, who noted that some small-scale wheeled robots are commercially available.

The robots could be used in practical applications in five years, said Adkins. The work was funded by Sandia National Laboratories.

Timeline: 5 years
Funding: Government
TRN Categories: Robotics
Story Type: News
Related Elements: None

Tiny Robots Flex Their Muscles

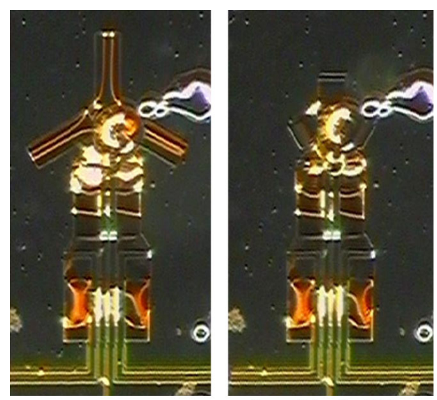
By Eric Smalley, Technology Research News
July 26, 2000

Researchers have produced tiny robot arms that work in salt water, a feat that makes the notion of swarms of microscopic robots performing medical procedures inside your body a little less fanciful.

The arms, developed by a team of researchers at the University of Linköpings in Sweden, are cousins of assembly line robots but with two important differences: they are very small, measuring 640 microns long — or about two-thirds of a millimeter — and they operate in liquids.

"Our principal application [will be] manipulation of biological entities like single cells, bacteria, and multicellular organisms in a lab-on-a-chip," said Edwin W. H. Jager, a graduate student and lead researcher on the project.

The researchers have gotten the microrobots to pick up and move a glass bead 100 microns in diameter. Human egg cells are 100 microns, red blood cells five microns and E. Coli bacteria one micron in diameter.



Source: University of Linkopings

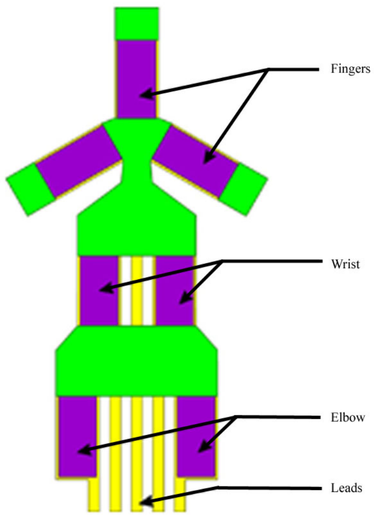
These images show a microrobot from below. In the left image, the robot's three fingers are open over a 100-micron bead. In the right image, the robot is grasping the bead.

"It is very exciting work," said Richard Yeh, a graduate student researcher at the Berkeley Sensor and Actuator Center at the University of California, Berkeley. "As far as I know, the microrobot is the first one to manipulate sub-millimeter-sized objects in an aqueous solution."

Given more precise equipment, the researchers' technique could be used to make microrobots one-tenth the size of the current version, Jager said. And in principle they could be made even smaller, he said.

Each microrobot consists of an elbow, wrist and two to four fingers, all made of microactuators. Microactuators are tiny strips of material that bend when a small electric current is applied to them. The microrobots' microactuators consist of a layer of polypyrrole, which is a conductive polymer, and a layer of gold. The polypyrrole shrinks when the current is applied. Because the gold does not shrink, the microactuators bend. The microrobots are designed so this electrochemical reaction occurs when they are immersed in salt water or other electrolytic solution.

The researchers made the robots by first outlining their shapes on a titanium-coated silicon wafer via the photolithography process used to make integrated circuits. Then they layered gold over the titanium. Next, they put a rigid plastic between the actuators. They then deposited a layer of polypyrrole on top of the gold to form the actuators. Last, they dissolved the titanium layer, freeing the microrobot.



The purple areas in this diagram are the robot's microactuators, whick serve as both muscles and joints. The green areas are rigid plastic. The yellow lines are electrical leads.

The microrobots could be used as minimally invasive surgical tools, said Yeh. They could also be used as miniature assembly line robots for building other microdevices, Jager said. The microrobots could be ready for commercial use in five to 10 years, he said.

The devices and their construction are described in a paper written by Jager, Olle Inganäs and Ingemar Lundström in the June 30 issue of the journal *Science*. The research was funded by the Swedish Research Council for Engineering Sciences and the Swedish Foundation for Strategic Research.

Timeline: > 5
Funding: Government
TRN Categories: Robotics; MicroElectroMechanical Systems (MEMS)
Story Type: News
Related Elements: Photo; Diagram; Technical paper "Microrobots for Micrometer-Size Objects in Aqueous Media: Potential Tools for Single-Cell Manipulation" *Science*, June 30, 2001

TRN

Self-Building/Self-Shaping

Self-Configuring Robot Mimics Lifeforms

By Ted Smalley Bowen, Technology Research News
January 24, 2001

Scientists have long looked to nature for models when developing machines — even machines that perform the unusual acts of pulling themselves apart and reconfiguring themselves.

Researchers from the University of Southern California have designed modular robots that move like snakes and spiders, and use a communication system akin to biological hormonal activity.

The self-assembling robots have the ability to rearrange themselves, and even exchange modules, making themselves bigger or more numerous, said Wei-Min Shen, an associate professor of computer science at the University of Southern California.

Eventually, this type of robot could change shape, size and locomotion method in order to navigate varied terrain or work in groups, traits that could be used for remote operations like search and rescue, and surveillance tasks, said Shen.

For instance, a robot could transform into a snake to pass through a narrow passage, rework itself to add legs to climb over an obstacle, and form a ring to roll quickly down a slope, according to Shen.

The robots are made up of identical, box-like modules constructed largely of off-the-shelf components. An individual module's functions are dictated by its position in a given configuration.

Each module includes a computer processor, batteries and a pair of motors that allow it to rotate up and down, and left and right. A single module can only wiggle on its own, but once two or more modules connect to form a structure, several different types of locomotion are possible, according to Shen.

The modules connect via one of four docking ports located on four sides of each module. The ports pair connectors with infrared communications systems that guide the connection process and allow modules to exchange hormone-like messages.

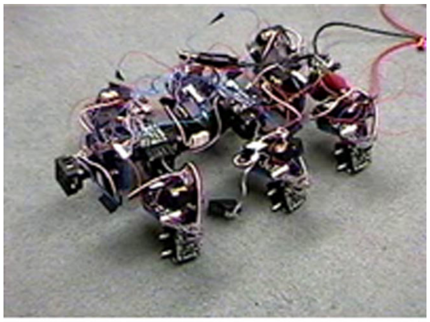
Connected modules communicate using these messages. In addition, modules from different robots can also communicate this way via open ports that are 30 centimeters or closer. This allows robots to coordinate actions and exchange modules.

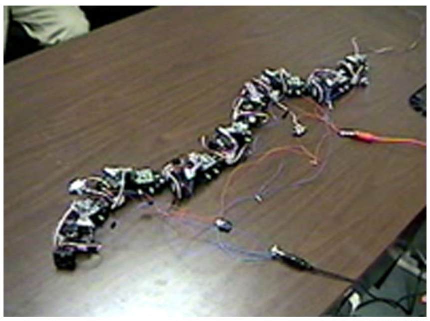
The researchers have created several different configurations using the modules, including a robot with a three-module body and six legs, and an autonomous snake, Shen said.

The robots are self-sufficient, meaning they use the distributed communications system to move on their own.

In addition, some of the robots are autonomous, meaning they can also reconfigure themselves without human intervention.

So far, autonomous robots constructed of the modules have been able to move only in snake-like fashion, but that should change, said Shen. "We are working to make all reconfiguration automatic," he added.





Source: USC

The first video shows an insect-like robot doing a push-up. The second video shows a robot moving like a snake. The interchangeable modules that make up these robots communicate via a hormone-like messaging system to coordinate their movements.

The autonomous snake can connect its head to its tail and form a loop in about three minutes, said Shen.

In addition, "a human operator can configure the robot any shape she wants with the four-way connectors on the modules," Shen said.

The key to the robot's self-sufficient and autonomous behavior is the hormone-like communication system, which allows modules to coordinate movements and reconfigurations.

The modules can broadcast messages to the other modules that make up a robot. These messages trigger the specific actions required for the robots to assemble, move and change shape.

Like biological hormones, the messages last only a certain length of time, trigger different actions in different receiving sites, and leave the execution and coordination of a local action to the module performing the action.

These properties are ideal for specifying tasks in a distributed system with minimal communications, according to Shen.

A module generates a hormone message when it receives a message from another module or from a human operator, or when its sensors detect certain conditions. "Every module can become a hormone generator, and can send out hormones to the entire network of modules," said Shen.

For instance, a snake robot module that contains a tilt sensor can keep the snake right side up, said Shen. "If this module detects that the snake is upside down, it will generate a sequence of hormones to other modules and the whole snake will perform a set wiggling to flip its body to the normal position."

The modules store generated hormones in a hormone template table. Each module typically has two or three template tables, a number limited by the size of the modules' memory, said Shen.

Hormone messages contain four variables, each of which has an expected range of parameters. The variables are HormoneType, ActionCode, ParameterValue and TimeToLive. Modules check each field's value against expected ranges, and discard hormones with erroneous values, Shen said.

As the hormone messages are passed between modules, the modules read them, follow their instructions to perform local actions, and, if needed, modify the messages and pass them on, or discard them when they reach their expiration date.

In cases when a number of hormones signal conflicting actions, a conflict resolution system determines the higher priority hormone.

"This is an interesting application of hormonal control to teams of robots working together. While others have explored hormonal control, I am not aware of other researchers who focused on multi-robot applications," said Ronald C. Arkin, professor and director of the Mobile Robot Laboratory at the Georgia Institute of Technology's College of Computing.

"Hormonal control provides a nice alternative to neural models of control for certain applications, specifically those which are often concerned with self-preservation and/or motional state," said Arkin. "Their use by this group to coordinate multiple robotic units is a nice extension of that idea."

The modular approach should lend itself to considerably larger robots, said Shen. "We can make a snake as long as we want. The snake can move in a caterpillar style. In principle, the size of the robot should not be a limiting factor for a successful reconfigurable robot, for it builds itself up as big as it likes," he said.

In order to make robots suitable for a range of environmental conditions, the researchers plan to modify the modules' housings. "We would like to make them waterproof, but that will be done in the future," Shen said.

The modular robot concept is general enough to have attracted the interest of a toy maker, in addition to the military, industrial and scientific communities, he said.

The researchers expect to have a workable, reconfigurable unit in roughly a year, according to Shen.

Shen's research colleagues on the hormone research were Peter Will, Behnam Salemi. Will and Andres Castano collaborated on the basic modular design, along with Ramesh Chokkalingam, Robert Kovac, and Behrokh Khoshnevis.

The researchers published a technical paper on the building block concepts in Proceedings of the IEEE/Robotic Society of Japan (RSJ) International Conference on Intelligent Robots Systems in Takamatsu, Japan, October 30-November 5.

They published a technical paper on the hormonal communication scheme in the proceedings of the International Conference on Intelligent Autonomous Systems in Venice, Italy, July 25-27, 2000.

The research was funded by the Defense Advanced Research Projects Agency.

Timeline: 1 year
Funding: Government
TRN Categories: Robotics
Story Type: News
Related Elements: Robot-as-insect video, Robot-as-snake video. Further videos available at www.isi.edu/conro/proto2SP.html; Technical paper "Mechanical Design of a Module for Reconfigurable Robots," Proceedings of the IEEE/RSJ International Conference on Intelligent Robots Systems October 30-November 5, 2000 in Takamatsu, Japan; Technical paper "Hormones for Self-Reconfigurable Robots," Proceedings of the Sixth ernational Conference on Intelligent Autonomous Systems, July 25-27, 2000 in Venice, Italy.

TRN

Evolution Trains Robot Teams

By Kimberly Patch, Technology Research News
May 19/26, 2004

Evolution has worked pretty well for biological systems, so why not apply it to the systems that control robots?

Evolutionary computing has been tapped to produce coherent robot behavior in simulation, and real robots have been used to evolve simple behavior like moving toward light sources and avoiding objects.

Researchers from North Carolina State University and the University of Utah have advanced the field by combining artificial neural networks and teams of real mobile robots to demonstrate that the behavior necessary to play Capture the Flag can be evolved in a simulation.

"The original idea... came from the desire to find a way to automatically program robots to perform tasks that humans don't know how to do, or tasks which humans don't know how to do well," said Andrew Nelson, now a visiting researcher at the University of South Florida.

The method could eventually be used to develop components of control systems used in autonomous robots, said Nelson. "Any task that can be formulated into a competitive game — like clearing a minefield or searching for heat sources in a collapsed building — could potentially be learned by a neural network or other evolvable [system] without requiring a human to specify the details of the task," he said.

Further off, the method could be applied to robots that must learn to operate in environments that humans don't understand well, said Nelson. "Currently autonomous robot control requires a human designer to carefully analyze the robot's environment and to have a very good understanding of exactly what the robot must do in order to achieve its task," he said.

The capture-the-flag learning behavior evolved in a computer simulation. The researchers randomly generated a large population of neural networks, then organized individual neural networks into teams of simulated robots that played tournaments of games against each other, said Nelson.

After each tournament, the losing networks were deleted from the population, and the winning neural networks were duplicated, altered slightly, and returned to the population.

"When they first start learning, [the networks] are unable to drive the robots correctly or even avoid objects or one another," said Nelson. "However, some of the networks are bound to be slightly better than others and this [is] enough to get the artificial evolution process started," he said. "After that, competition will drive the process to evolve better and better networks." During the course of their evolution, the neural networks learned basic navigation, the ability to distinguish between different types of objects, and the ability to tend the goal, according to Nelson.

After several hundred generations, the neural networks had evolved well enough to play the game competently and were transferred into real robots for testing in a real environment. "The trained neural networks were copied directly onto the real robots' onboard computers," said Nelson.

Source: North Carolina State University

These robots can play capture the flag. Their game-playing ability was learned through an evolutionary process in simulation and then downloaded to the robots.

One of the main challenges in carrying out the process was making sure the simulated environment was similar enough to the real environment so that the networks could function in the same way in both, said Nelson. The robots used color video signals to sense their environment. In order to support color video signals, which carry a lot of information, the researchers had to use relatively large neural networks containing thousands of connections. "We had to find a way of processing video signals that would allow for simulation but still provide enough information [to] operate the robots," he said.

Another challenge was formulating an evolutionary training method that fostered competition both between populations of new, very poorly performing networks and between well-trained, highly-evolve networks, said Nelson. "We wanted the networks to be selected for reproduction based only on their ability to win, but not on any of our own personal human ideas about how to go about winning," he said.

There were several surprising results, said Nelson. In many neural network applications, the larger and more complicated a network is, the more difficult it is to train, he said. "In contrast... we found that the larger the network was, the easier it was to train. This could potentially be attributed to the use of artificial evolution to train the networks," he said.

The researchers also found that after a certain level, increasing the size of the evolving population did not result in evolving better networks. "With the form of artificial evolution we used, a population of 100 networks did not evolve better players than a population of 30 individuals," said Nelson.

The researchers are working to improve the quality and speed of the simulations in order to apply the research to more sophisticated problems. "One possible approach is to apply very fast high-fidelity computer gaming engines to develop robot simulation environments," said Nelson.

The method is also likely to throw light on the question how well artificial systems can learn complex behavior, said Nelson. "Is there a plateau beyond which blank-slate systems cannot be trained using interaction with the environment alone?"

Evolving entire control system components for modules used in today's robots is possible, but not practical, because human-designed controllers are still more efficient than evolved controllers for most of the simple tasks autonomous robots perform, said Nelson.

The method could be used to automatically tune well-defined components of robot control systems, said Nelson. "For example, a robot might retune its object avoidance mechanisms upon entering a new environment — outdoors vs. inside," he said. This could be used practically in three to six years, he said.

The long-term benefit of evolutionary robotics research is that it may lead to controllers for robots that can automatically adapt to unknown environments, said Nelson. This ability is many years off, however — more than 10, and perhaps as many as 50 years, he said.

Nelson's research colleagues were Edward Grant of North Carolina State University and T. C. Henderson of the University of Utah. The work appeared in the March 31, 2004 issue of *Robotics and Autonomous Systems*. The research was funded by the Defense Advanced Research Projects Agency (DARPA) and the University of North Carolina.

Timeline: 3-6 years; 10-50 years
Funding: Government; University
TRN Categories: Robotics; Artificial Life and Evolutionary Computing; Neural Networks
Story Type: News

Related Elements: Technical paper, "Evolution of Neural Controllers for
Competitive Game Playing with Teams of Mobile Robots," *Robotics and Autonomous Systems*, March 31, 2004

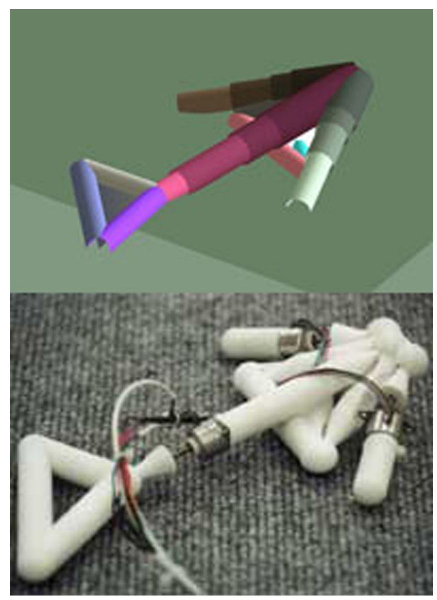
Robots Emerge from Simulation

By Eric Smalley, Technology Research News
September 20, 2000

Living things have at least two advantages over machines — we reproduce and we are honed by millions of years of evolution. Researchers at Brandeis University have developed a system for designing robots that makes it clear those advantages are destined to fade into history.

The researchers' Genetically Organized Lifelike Electro Mechanics (Golem) project combines a genetic algorithm that allows populations of virtual robots to evolve toward a desired set of characteristics, with a rapid prototyping machine that builds the robots' body parts automatically.

The long-range goal of the project is to reduce human involvement in the process of building machines like robots to defining their tasks and supplying the raw materials to build them, said Jordan B. Pollack, associate professor of computer science at Brandeis.



Source: Brandeis University

The virtual robot "Arrow" (top image), the result of hundreds of generations of simulated evolution, served as the blueprint for the physical robot "Arrow" (bottom image), whose body was built automatically using a rapid prototyping system.

The general idea was "evolving [robot] bodies and brains together in simulation and then trying to figure out how to transfer them to reality," he said. The solution was to make the robots' body parts emerge from a vat of liquid plastic via stereo lithography, a rapid prototyping technique that uses computer-controlled lasers to set the light-sensitive liquid.

Postdoctoral researcher Hod Lipson developed the "universal robot set" starting point for the genetic algorithm by adding motion to a truss simulator, Pollack said. Truss simulators model the components of structures like bridges.

The genetic algorithm started with a population of 200 virtual machines and selected those that were best at moving. The algorithm replicated the selected individuals, modified the copies and then added them into the population in place of other individuals, sometimes randomly and sometimes in place of the least fit. The algorithm repeated the process 300 to 600 times.

The robots the system built are little more than toys. They consist of plastic tubes and joints and electric motors. The motors have to be inserted by hand. The robots are less then a foot long and their bodies are combinations of simple geometric shapes. (See photo)

The machines' only task is to move in one direction on a horizontal surface. But the simple devices demonstrate a process of combining automated designed with automated manufacturing.

Pollack and Lipson "have opened a new way of designing systems whereby one doesn't have to look at past experiences," said Pradeep Khosla, Dowd Professor of engineering and robotics at Carnegie Mellon University. "The structures that come out of [the simulations] are not totally intuitive."

For example, one of the robots is roughly pyramid shaped with a rod in the center. The rod presses downward at angle, shuffling the machine forward.

The next phase of the Golem project is to increase the complexity of both the robots' components and their tasks, Pollack said. The researchers plan to use robotic arms to assemble the next generation of the robots from existing parts, he said. Pollack is also working on projects aimed at giving robots the ability to learn and adapt once they're on the job.

"You don't expect a transfer from simulation to reality to work. You expect it to be a noisy sort of process that gets you most of the way there but doesn't really give you a working robot," Pollack said.

The automated design and manufacturing system could be used to produce useful machines in seven years and could be used to make toys in two years, Pollack said. Pollack's work on evolutionary computing is funded by the Office of Naval Research. The Golem project is funded by DARPA. The researchers publish their work in the August 31, 2000 issue of the journal *Nature*.

Timeline: 7 years
Funding: Government
TRN Categories: Artificial Life and Evolutionary Computing; Robotics
Story Type: News
Related Elements: Technical paper "Automatic Design and Manufacture of Robotic Lifeforms", *Nature*, August 31, 2000

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