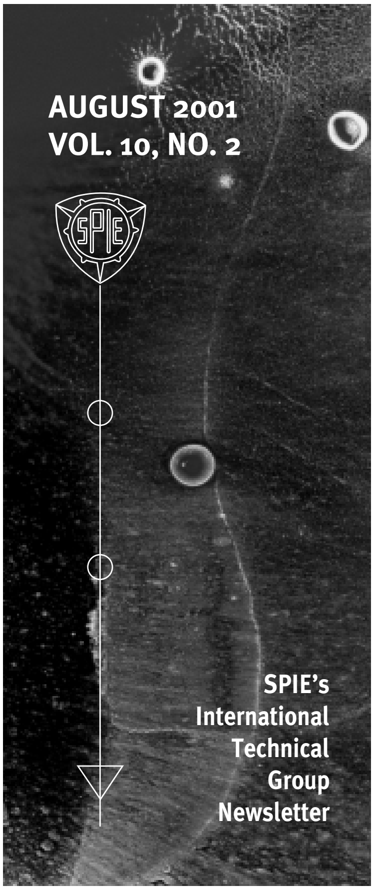

Calendar *—See page 9*

Technical Group Reg Form
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Newsletter now available on-line

Technical Group members are being offered the option of receiving the Robotics and Machine Perception Newsletter in an electronic format. An e-mail notice is being sent to all group members advising you of the web site location for this issue and asking you to choose between the electronic or printed version for future issues. If you have not yet received this e-mail message, then SPIE does not have your correct e-mail address in our database. To receive future issues of this newsletter in the electronic format please send your e-mail address to spie-membership@spie.org with the word ROBOTICS in the subject line of the message and the words "Electronic version" in the body of the message.

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Robotics and Machine Perception

Perceiving human environmental preference through adapted fuzzy neural networks

Because human beings are individuals, they each have their own preferences for how the environment around them should look and feel. Variables such as temperature, light, humidity, sound volume, toast browning and access, to name but a few, are adjusted to individual preferred levels in millions of homes, offices and cars to match their changing moods, needs, and external conditions. Many of these processes are automated, however they all require user interaction with the system. Because our lives have become more gadget- and electronics-dependent, the cognitive load on us increases. To reduce this load, methods need to be devised that can learn, understand, and update knowledge of human preference. Apart from making technology easier to use, there are also tangible money savings to be made: for instance previous research into the field of Intelligent Buildings (IB) has concluded that, in an office environment, up to a 40% saving of energy costs can be achieved by automating environmental control.[1]

The Intelligent Dormitory (iDorm)

The Intelligent Inhabited Environments research group at the University of Essex is researching a variety of solutions to the problem of how best to perceive a user's environmental preference. Our most recent work is towards the creation of an iDorm agent to perceive user preference and adjust the room environment to meet it.

There are three stages to this work. The first is the creation of a student dormitory using the same furniture and fittings as those found in the halls of residence at the University of Essex. This was achieved by re-fitting a room in the Computer Science Department. The second stage, now nearing completion, is discreetly adding the sensors and effectors to the room to enable an intelligent agent to monitor and make changes to the room's environmental conditions. The sensor network includes the following devices: a matrix of temperature sensors both inside and on the outside of the room to provide detailed thermal environment data to the agent; humidity and temperature sensors for the environment outside the wet wall; a small matrix of light sensors across the room; an active entrance lock system that provides access based on an individual's identity; an infrared sensor to detect movement; and a video camera to externally monitor the room.

Currently, a number of effectors connected to the same networks are also in the process of being installed. These include: air circulators, fan heaters, a door lock actuator, motorized vertical blinds, automated window openers and a light dimmer.

The majority of the sensors and the effectors are off-the-shelf solutions from Lonworks, an industry standard in IB solutions that uses its own LonTalk network to communicate.[2] The remainder of the devices are linked via IPv4 using Dallas Semiconductor's embedded Internet TINI boards.[3] The predicted final layout of the room can be seen in Figure 1.

The way the iDorm network is set-up means that the status of the effectors can be monitored and adjusted by both the user and the network that connects them. That is, should a user choose to close the blinds or dim the lights, the agent can detect this activity and the set levels. In the same way, the agent can make changes to

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Editorial

Welcome to this issue of the Robotics & Machine Perception Newsletter. The articles in this issue bring together a wide range of topics in robotics sensing and control for a range of system and application scenarios. We are particularly pleased to include in this issue an overview of intelligent robot trends from Professor Ernest Hall. Professor Hall surveys past and future trends in intelligent robotics and emphasizes the importance of education and research in the innovative development of new robotics concepts and applications.

The remainder of the articles in this issue reflect the diversity of current research activity in robotics, including techniques for mapping and localization in the articles by Branca et. al. and Nicholson, cooperating and team robot strategies in the articles by Campos and Murphy, modular approaches for behavior integration and cross-application reuse of behaviors and sensing strategies in the article by Sukhatme & Dedeoglu, and finally the integration of sensing and control strategies with AI techniques for intelligent home environments in the article by Pounds-Cornish et. al. We hope you enjoy reading the articles and we encourage you to pursue the references provided for further information and background to the topics presented.

I would like to take this opportunity to remind you also of the forthcoming Intelligent Systems and Advanced Manufacturing (ISAM) symposium, part of SPIE's Photonics Boston meeting, 28 October-3 November, 2001. ISAM includes conferences on computer vision, sensor fusion, mobile robots, telepresence technologies and micro-robotics. Your participation in these conference is most welcome. Further details can be obtained at the SPIE web site.

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Intelligent robot trends

Intelligent robots are an ideal, a vision. To see a model, look in a mirror. Intelligent robots are also a reality. Robots are making measurements on Mars, aiding physicians in hospitals and working in industry. Many intelligent robot prototypes have been built: typical applications include high speed spot and seam welding robots, spray-painting robots, material-handling and assembly robots, and robots loading and unloading machines.

The components of an intelligent robot are a manipulator, sensors, and controls. However, it is the design architecture of these components—the paradigms programmed into the controller, the foresight and genius of the system designers, the practicality of the prototype builders, the professionalism and attention to quality of the manufacturing engineers and technicians—that makes the machine truly intelligent.

Figure 1. Students from BEST program enjoy the Bearcat II robot.

In economic terms, robotics now represents a billion dollar market, and cheaper robots are proving increasingly good investments. A cost estimate was made from data from the RIA[1] records for the first quarter of 1999, and indicated that $362.8 million in new orders for 4732 robots, giving an average cost of $76,864. Another estimate from application feasibility studies for a variety of applications done by engineering students gave average robot cost from 14 different applications of $69,141 with the average internal rate of return of 98%.

Mechatronics: becoming recognized

Mechatronics is a methodology used for the optimal design of electromechanical products.[2] The mechatronics system is multi-disciplinary, embodying four fundamental disciplines: electrical, mechanical, computer science and information technology. Mechatronics is necessary in order to understand the modeling and simulation of physical systems, sensors and transducers, actuating devices, hardware components, signals, systems and controls, and real-time interfacing. There are now new robot manipulator designs, and robots are faster, smaller, more repeatable, safer and easier to use.

- In 1985, the four common types of robot manipulators were the Cartesian, cylindrical, spherical and vertically articulated or anthropomorphic designs. Then, the horizontally-articulated or Selective Compliant Articulated Robot for Assembly (SCARA) was introduced. In 1995, a Stewart platform with a very different design, a tricept, was displayed at the Robot and Vision Exhibition by Comeau. It was advertised as being as flexible as a robot, as precise as a machine tool, and strong as a press. It seemed ideal for press-fitting bearings and other tasks requiring thousands, rather than tens or hundreds, of pounds of force.
- Rotational speeds of robot manipulator links of 240°/second are now typical. For a 1m joint length, this produces linear speeds of 4m/second. The overall cycle time is usually more important than individual link speeds. In a great variety of applications, robots are easily made as fast or faster than humans.
- In terms of size, micromechanical manipulators, molecular robotics, nanorobotics are names applied to the emerging field to produce new materials and devices at a nanometer scale, perhaps by direct interaction with atomic structures.
- The repeatability of an industrial robot refers to its ability to return to a previously taught point in space with a certain precision. Typical repeatability is about ±0.1 mm (±0.004 inch). Accuracy is the ability to go to a target point in space and generally can be achieved with a calibration setup.
- Both industrial robots and automated guided vehicles are potentially dangerous since they move. Industrial robots in the U.S. have killed people. Safety requires administrative controls, engineering controls and training.
- Using an industrial robot is easy but putting it into an intelligent work cell requires much more than the robot. Important accessories such as grippers, process tooling, safety devices, programmable logic controllers, simulation programs, etc. are needed to make robots easier to use.

Continued progress

Open architecture controls are increasingly common. The control system is the set of logic and power functions that allows the automatic monitoring and control of the mechanical structure and permits it to communicate with the other equipment and users in the environment. Open architecture control refers to software designs that can use or be used with products from a variety of manufacturers.

On the theoretical side, inverse kinematic solutions, inverse dynamic solutions, and experimental designs are making a contribution. Most industrial robots are operated in position control mode, as contrasted with velocity or force control. To move the motors to position a robot manipulator in space, an inverse kinematic solution is needed. The inverse kinematic solution must be discovered for each new manipulator design. New symbolic solutions provide results that can be used by anyone.

Also, even though industrial robots are position control devices, the path between position points can be extremely important, for example, in seam welding. Since any moving system is described by a dynamic differential equation according to Newton's Second Law, the dynamic solution must also be determined in the design of a robot and in the design of the control system.

Integrated robots with vision and sensors also represent a step forward. For the industrial robot to be intelligent and adapt to changes in its environments—such as part location, orientation, size, shape—sensors are needed. Vision is the most powerful sensor for humans, and machine vision also adds adaptability to industrial robots that makes them intelligent. The combination of robots and vision with motion control is a trend toward understanding all the components of the intelligent robot, the manipulator, the sensors and the controls.

Other important tools for roboticists are simulators and code generators. In the design of a robot work cell, a three-dimensional simulation permits one to observe interference, avoid collisions and determine feasibility of an operation. In some modern simulation software, once a series of motions are selected, the robot code generator program can translate the motions into robot programming language automatically and download this program to the robot.

Applications

Automatically-guided vehicles are becoming more feasible in factory automation. The development of practical and useful unmanned autonomous vehicles continues to present a challenge to researchers and system developers. The service robot area is also growing. The International Service Robot Association is an individual and corporate member organization devoted to the application of robot technology to human ser-

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Heterogeneous multi-robot cooperation

The Vision and Robotics Laboratory (VER Lab), at the Department of Computer Science of the Federal University of Minas Gerais, Brazil, has been performing research in several areas related to autonomous robotics. In recent years, the focus has been on cooperation among multiple heterogeneous robots navigating in different media. The motivation behind this research the challenge of efficiently monitoring large environmental areas such as those found in Brazil.

We have been specially interested in both loose and tight cooperation of multiple robots of different kinds. Some of the issues are being tackled both in simulation and by implementation with real robots that move in different media such as air and on the ground. The mobile robots we are currently working with are commercially available models and low cost, autonomous vehicles—both aerial (dirigible) and small robots equipped with different sensors—built in-house.

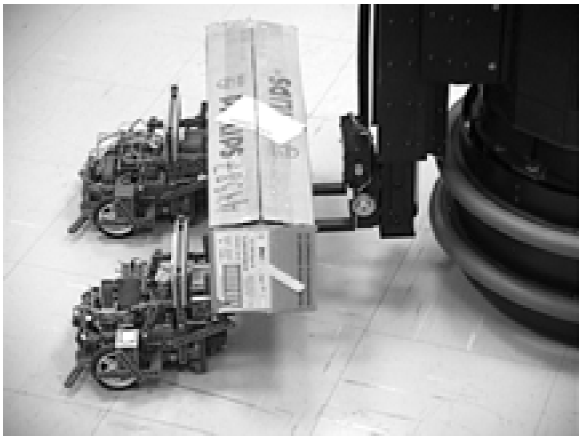

Figure 1. An autonomous blimp guides two small robots in a tight cooperative task.

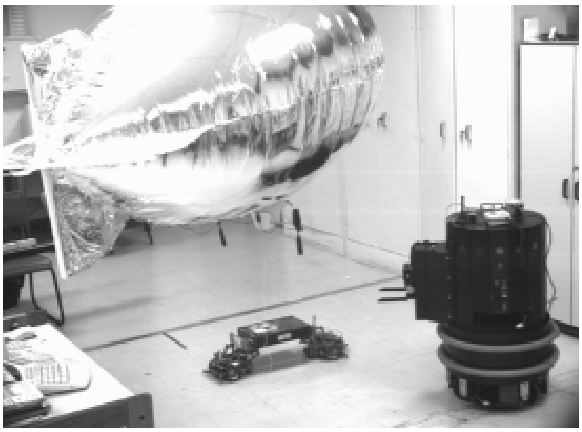

Figure 2. Two small robots deliver a box to a Nomad 200.

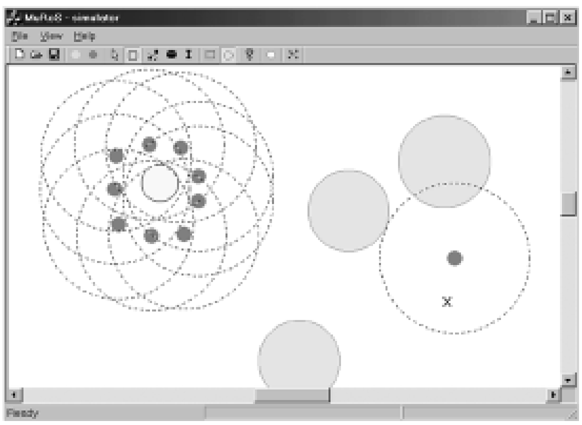

Figure 3. MuRoS, the Multi-Robot Simulator.

Autonomous dirigibles

One of the greatest current challenges is broad and intensive environmental monitoring and surveillance. These tasks impose tough demands on aerial autonomous robotics. Considering several factors discussed elsewhere,[1] dirigibles are natural candidates for the job.

Autonomous, indoor, small-scale (2.1m) indoor dirigibles equipped with onboard micro-cameras were developed at VER Lab as testbeds for vision-based navigation[2] and co-operation. Our system is currently able to perform precise pose estimation with respect to a starting point, and proceed with navigation from there. There are several restrictions on small robots that are specially related to their non-holonomic characteristics, low-power actuation system, and reduced payload. However, scaled-up versions of those vehicles—capable of autonomous, long-endurance reconnaissance and monitoring flights over rain forests and other hard-to-reach areas in Brazil—are currently being developed and field tested in collaboration with the Institute for Information Technology in Campinas.

Cooperation issues

One of our goals is to achieve cooperation among several aerial autonomous vehicles in both loose and tight cooperation tasks. Small, light-weight, force sensors are currently being built to measure tension forces on the cables of two indoor dirigibles transporting a small load. Coordinated navigation of the autonomous blimps is complex and includes difficult problems such as load stabilization during flight: precise placement of the destination and compensation of lateral forces generated by the load pulling both cables normal to the flight heading.

Small, low cost mobile robot for cooperation

Aiming at both flexibility and low cost, several small autonomous robots based on Lego building blocks and equipped with a micro-controller (Handy Board) were successfully built at VER Lab. These rugged robots are equipped with several sensors—including force sensors (built in-house) and cameras—and are able to perform tight cooperation (such as coordinated box-carrying tasks) dynamically while avoiding obstacles and with minimum or no explicit communication. These small agents cooperate among themselves and with the Nomad 200 mobile robot (see Figure 1).

Figure 2 depicts the cooperation among four heterogeneous robots. Using a vision-based feature-tracking algorithm, the autonomous blimp provides global direction to the two small robots carrying a box to be delivered to another larger robot (Nomad 200). Communication between the dirigible (its ground computer actually) and the small robots is established via radio-modem, whereas ethernet is used to communicate with the Nomad 200.

MuRoS

MuRoS[3] is a multi-robot simulator and environment developed in collaboration with Prof. Vijay Kumar, GRASP Lab, University of Pennsylvania, USA. This simulator effectively implements an architecture for tight cooperation. New strategies can easily be tested by letting the user specify the environment as having general obstacles and defining the specific robot's features, as seen in Figure 3. This simulator will soon be enhanced to be able to cope with co-operation in 3D.

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Sensor failure recovery through distributed surrogate sensing and reconfiguration

The marsupial concept was initiated in 1996 with funding from the National Science Foundation, leading to a mother constructed from a children's battery-powered jeep that could carry a single, tethered micro-rover. The target domain was Urban Search and Rescue (USAR), where robots may need to be sent over 50 meters to a collapsed building. Micro-rovers would expend most of their battery power just reaching the rubble. Under the DARPA Tactical Mobile Robots program, a new team was created from a RWI ATRV—modified to carry three RWI Urban micro-rovers—and the application domain expanded to include military operations in urban environments (MOUT). We have demonstrated autonomous deployment and docking of the daughters[2] and collaborative teleoperation, where a secondary robot assists a teleoperator by providing an external view of the target robot situated in its environment. This is extremely useful for robots working in rubble, where they can become easily trapped or high-centered on a rock, because the teleoperator cannot determine the problem strictly from the onboard camera or other sensors.

As a result of our experience in working in rubble and collapsed buildings at various Fire Rescue training sites throughout the country, our work has begun to consider robustness a key aspect of a truly field-ready system. A major problem we have encountered is sensor failure from debris or dirt covering a camera or other sensors. The need to recover from sensor failures has led us to identify another advantage of marsupial robots: the ability of the mother robot to dynamically adapt to sensor failures by using a daughter robot as a surrogate sensor.

For example, consider the following sequence. The USF mother robot is tracking and moving to intercept a colored fiducial marker. She has one daughter robot onboard. In Figure 1, the mother's camera mounted on top is unplugged, creating a sensor failure. The mother has no backup camera onboard, but can use daughter's camera as a surrogate. The daughter's camera is facing forward in the bay just below the mother's camera in the middle of the row of sonar disks. In Figure 3, the daughter's camera is now covered by cloth. The daughter's camera is still functional so the mother turns around, and in Figure 4 deploys the daughter, which then backs into the bay so that her camera faces backward. Figure 5 shows the mother resuming tracking and navigation, just going backwards using the daughter as a surrogate sensor again. This case illustrates both surrogate sensing and reconfiguration of the onboard daughter. Another example is to have a transitive distributed arrangement where the daughter robot is deployed in front of the mother. The daughter leads using a preferred sensor while the mother follows the daughter using a more restricted sensor.

Figure 1. The mother's camera mounted on top is unplugged, creating a sensor failure.

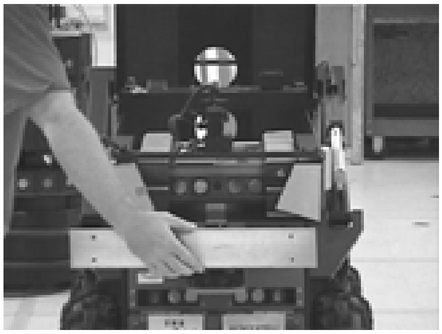

Figure 2. The mother uses daughter's camera (in the middle of the upper row of sonar disks) as a surrogate.

Figure 3. The daughter's camera is covered by cloth, but is still functional, so the mother turns around.

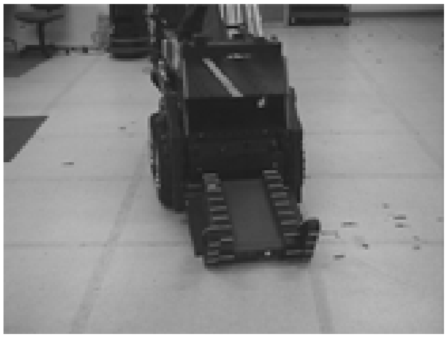

Figure 4. Next, she deploys the daughter, which then reverses into the bay so that her camera faces backward.

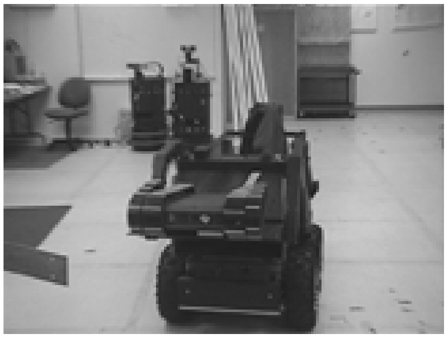

Figure 5. Now the mother resuming tracking and navigation, going backwards, using the daughter as a surrogate sensor again.

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Underwater vehicle navigation

We are working with an autonomous vehicle that moves deep in the sea to inspect pipes positioned near the ocean floor. We won't discuss the control algorithms to be used on the vehicle here, but rather we describe how to recover the information from which a guidance or navigation strategy can be constructed. This problem is particularly relevant to off-shore engineering, where underwater vehicles are already used for visual inspection of pipelines and other submerged structures. Such tasks are often very expensive and tedious, requiring the attention of human operators for long periods of time in order to manoeuvre the vehicle in murky waters in and in the presence of large hydrodynamic forces. This has recently motivated extensive research in ocean-related technologies towards the realization of autonomous vehicles. Various devices have been developed for determining orientation, altitude, and long- to medium-range positioning using acoustic and laser technologies.

Generally, reliable short-range horizontal positioning is difficult to achieve, particularly near the flat ocean bottoms. Doppler acoustic methods using dead reckoning are subject to significant drift. Other inertial navigation systems using accelerometers suffer from the same drawback in determining horizontal displacements. One effective solution to this problem is to use optical sensors.

In our context, the basic behavior required of the vehicle is to follow the pipe autonomously—performing online adjustments to its navigational path when deviated by large hydrodynamic forces—and to avoid obstacles. A solution based on pipe-tracking alone will fail when the pipe disappears in regions where it is covered by sand or gravel. Moreover, identifying some known features to be tracked, such as surface textures or edges, is difficult because—depending on events of nature—the surface texture changes continuously and the edges are rarely approximated to straight lines. Since the path along which the pipe is positioned can be known *a priori*, the problem can be reduced to a trajectory-following problem, where the pipeline path is the prescribed trajectory, and the motion estimates are used to maintain this trajectory.

However, estimation errors must be dealt with. Integrated over time, these could affect the corrected position of the vehicle, thus allowing it to deviate from the true path and lose the pipeline. Thus, an optimal approach must incorporate both visual egomotion estimation and correction based on pipeline tracking. Here we consider only the path correction based on the estimated visual egomotion. A particularly efficient solution to the problem of determining the motion would exploit the same images used for performing the inspection. Such a solution would facilitate the realization of automatic navigation and guidance systems for such vehicles, and greatly contribute to reducing the cost of inspections.

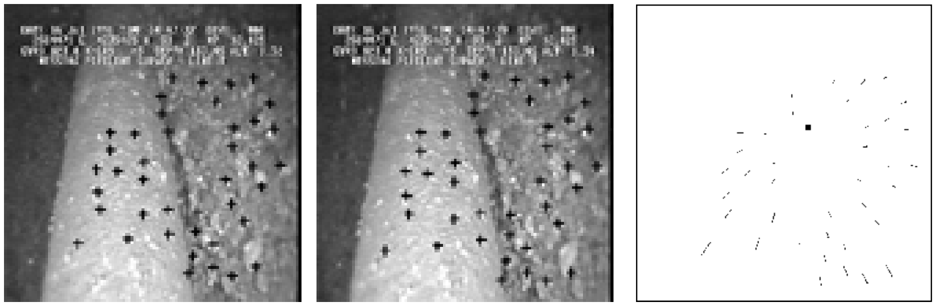

Figure 1. Tx=-0.0063 Ty=0.0077 Tz=0.0457 R=-0.0069 S1=-0.0033 S2=-0.0058.

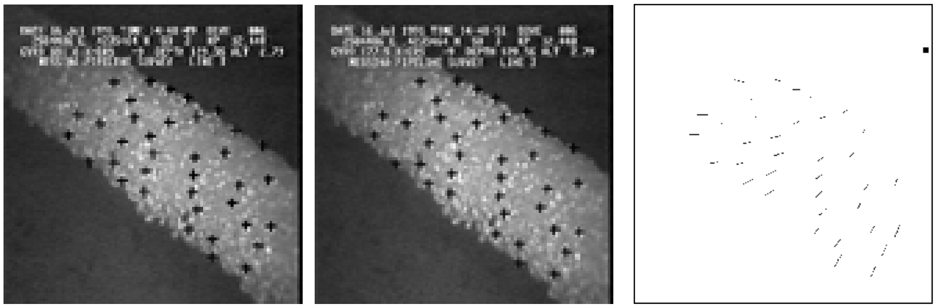

Figure 2. Tx=-0.0271 Ty=0.0112 Tz=0.0273 R=0.0072 S1=-0.0045 S2=0.0019.

It is well known that a significant amount of useful information about 3D motion can be obtained from 2D image motion using the projection onto the image plane. In underwater contexts, 2D image motion can be approximated by few correspondences found among significant features extracted from the temporal image sequence. We consider the salient image points recovered by the Moravec interest operator[1] at corners and edges as the relevant features to be matched.

The correspondence problem is solved by searching for a solution in the space of all potential matches, selected on the basis of their radiometric similarity, by requiring that global constraints derived from the projective geometry be satisfied. The vehicle is equipped with a front-look camera at an inclined angle relative to the horizontal plane of the pipe surface. The most remarkable structures observed in such underwater scenes (ocean floor and pipe) can be roughly assimilated to planar surfaces. For this reason, we impose the projective invariance of the cross-ratio[2] of five coplanar points as a global constraint in the matching process. We formulate the matching problem using graph matching theory. Optimal matches are recovered by searching the association graph—which consists of nodes representing candidate matches selected by radiometric similarity, and five-order links weighted by cross-ratio similarity—through an optimization approach based on iterative non-linear relaxation labeling.[3]

The relaxation labelling process outputs the largest number of mutually compatible (maximum clique) features. In our context, this will correspond to the largest set of coplanar and correctly-matched features, allowing the purging of all spurious features selected outside the pipe surface or on small moving objects (like fish).

The displacement field computed in this way is used to determine the 3D parameters describing the vehicle motion.[4] Corresponding perspective projective coordinates of points belonging to a planar surface, when observed from two different points of view while the vehicle is moving, are related by a linear projective transformation. This collineation, called homography, is completely specified by a 3×3 transformation matrix and is a function of the rotation and translation of the plane parameters between the two views. The method we use to estimate the 3D egomotion is based on the characterization of the coefficients of the homography matrix as functions of the 3D motion parameters.

In fact, due to the relatively small aperture of a typical imaging device with respect the focal length, in our context the collineation is reduced to an affine transformation. This allows for a linear description of the 2D motion field expressed as a linear combination of six elementary motions, whose coefficients are the 3D motion parameters representing respectively: translation along X axis (Tx), translation along Y axis (Ty),

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Intelligent autonomy

"Systems-of-systems will, in the 21st Century, replace every major combat system on the battlefield with distributed robots—in the air and on the ground, autonomous, net-centric, and integrated."
—Unknown DARPA Source

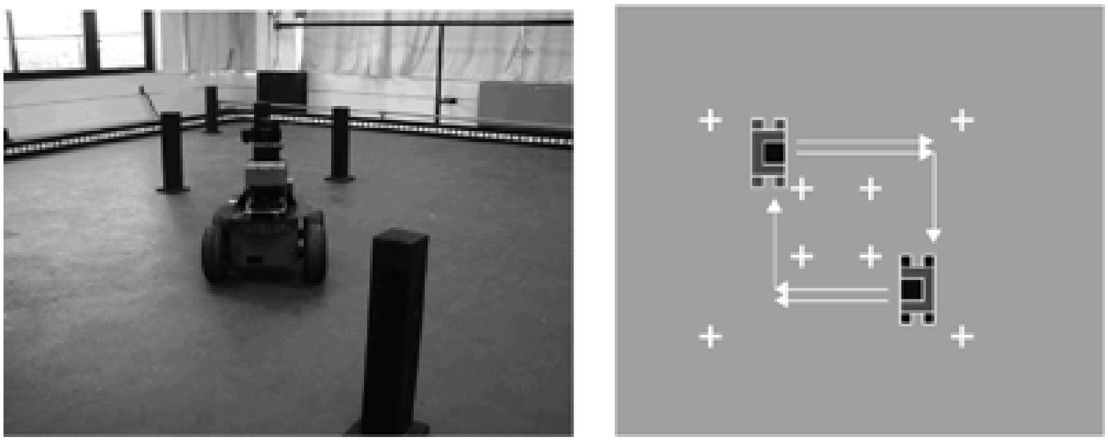

Figure 1. A snapshot from a lab-based SLAM experiment is shown on the left. This is displayed in schematic plan view on the right. The two robots sense features (indicated by crosses) in the lab environment and incorporate them into a global map. Each robot fuses the other's map by employing a fully decentralized form of the SLAM filter.

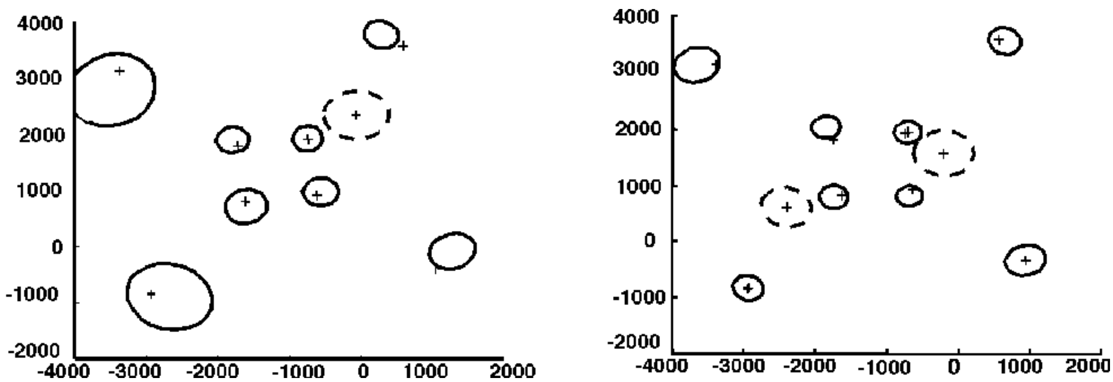

Figure 2. Experimental results: crosses mark the actual position of features placed down in the lab. SLAM estimates of these features are shown as solid uncertainty contours, the vehicle position estimates are indicated by broken contours. Notice the decentralized SLAM's improved map estimates.

This vision is driving much of the current robotics research in government and defense laboratories around the globe. Its realization will require a demonstrable capability in Intelligent Autonomy (IA), i.e., "The capability to operate effectively, singly or in groups, with reduced, remote (geographically or temporally) or no human command and interaction, and the ability to adapt independently to a changing, uncertain, unpredictable and hostile external environment."

BAe Systems, through its Advanced Technology Center in Bristol (UK), is currently investigating two fundamental aspects of the IA problem. These are Simultaneous Localization and Map Building (SLAM) and Decentralized Data Fusion (DDF), defined as follows. SLAM: A robot enters an unknown environment without a map and without knowledge of its own position. SLAM technology can enable a map to be constructed and to be used, simultaneously, for the purposes of navigation. DDF: A multi-sensor network is configured with no central fusion site or no central communication facility. DDF technology enables the system to build a robust and distributed tactical picture of the target environment.

SLAM contributes to IA by reducing a vehicle's dependence on GPS data and an accurate on-board terrain map. Neither of these two things can be guaranteed in practice (e.g., jungle or urban warfare scenarios). DDF contributes to IA by empowering individual vehicles to form their own global pictures, without having to rely on special input from a fusion center. The SLAM and DDF algorithms are formulated rigorously in terms of estimation theory and Shannon/Fisher information theory. Moreover, they can be subsumed in a more general theory of Decentralized SLAM.

One interesting result of Decentralized SLAM theory is its prediction of a super-linear speed-up effect. N vehicles produce a fused map in time T/N that is more accurate than the map produced by a single vehicle in time T. This is a rare example in distributed data processing where the law of diminishing returns does not appear to operate. This effect is present in closed-form solutions to the 1-D SLAM problem, but what happens in practice? A laboratory experiment in which the effect has actually been seen is illustrated in Figure 1. The simple experiment involved two robots sensing their local environments (but not each other), building maps, communicating data with each other, and producing fused maps.

The main experimental result is shown in Figure 2. This presents vehicle and map estimates, displayed as one sigma uncertainty contours, for a single robot SLAM run (eighty time-steps) and a double platform decentralized SLAM run (forty time-steps). It is evident that the double platform SLAM map is more accurate than the corresponding single platform SLAM map.

This result can be explained in terms of information balance. The SLAM filters acquire information through sensor measurements, and lose it through the accumulation of process noise between sensor updates. The single and double platform SLAM filters acquire an equivalent amount of sensor information. However, the performance of the double platform SLAM filter is degraded less by process noise. This is because the process noise has less time to accumulate and it is also independent between the vehicles.

In addition to its lab-based investigations, BAe Systems is also funding the University of Sydney (Advanced Field Robotics Center) to undertake the development of a multiple flight vehicle demonstration of DDF and SLAM.

It is our belief that Decentralized SLAM will be one of the cornerstones of practical and intelligent autonomy. However, the subject is still in its infancy and there are many outstanding chal-

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Perceiving human environmental preference through adapted fuzzy neural networks

continued from cover

the user's environment.

The third phase of work concerns embedding agents into more general and personal artifacts in a project called eGadgets but that is beyond the scope of this article.[4]

The iDorm Agent

Our design for the agent is as follows. The agent will sit between the sensors and the effectors in the room (see Figure 2). When a user makes an adjustment to the environment through the effectors in the room, the agent will take a "snapshot" of the current environment in the form of a list of the sensor values at that moment. The agent will use these values as inputs (after pre-processing) to a specialized evolving fuzzy neural network (EFuNN). The EFuNN used is being extended and adapted from initial research by Prof. Nikola Kasabov[5] who is collaborating with Essex on this work. The outputs of the neural network will be connected to the effectors in the iDorm and thus provide a control loop where the agent is able to translate user action into an environmental preference.

EFuNNs have the ability to store case-based (IF THEN) rules as part of the neural network structure, without destroying previously learned data. We are intent on using this feature to allow user preference data to be stored in different EFuNNs indexed by temporal information: for example the agent could use a different EFuNN to store user preference for "day" and "night". This feature also allows a human to understand what the agent has learned by viewing its knowledge base in the form of IF THEN rules.

Another benefit of this structure is the ability to add these case-based rules to, or remove them from, the neural network. We are aiming to use this feature to split the agent's knowledge base into a set of EFuNNs representing knowledge at different fuzzy temporal states. For example, the agent would have a knowledge base for a user's morning environmental preferences gleaned from a subset of all the data it knows. It can load this representation into working memory at the appropriate time. This modularity keeps the current neural network small and keeps operating speed high. It also allows the iDorm agent to store knowledge over extensive periods of time without losing detailed knowledge.

The goals

We are working towards an agent that will continuously update its knowledge about the user's preference such that the user will eventually have to interact with the environment only in unusual circumstances. In our approach we emphasize computationally compact and distributed AI methods, together with non-intrusive and individualized learning that can be seen as complementary approaches to other notable projects such as Mozer's Neural House,[6] Coen's HAL project[7] and Davidsson's Villa Wega.[1] Other work in the field includes that of the Future Computing Environments (FCE) Group at Georgia Institute of Technology.[8] The iDorm agent has the potential to make an environment more economical and limiting the resources it uses. It also has the potential to improve the quality of life for people who require long-term care by providing autonomous environmental management.

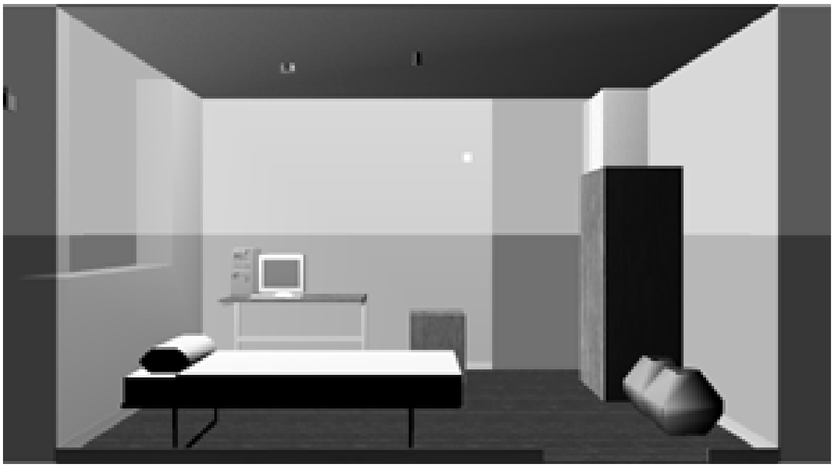

Figure 1. A screenshot of the iDorm VRML model used to prototype the layout of sensors, effectors, and furniture (to scale).

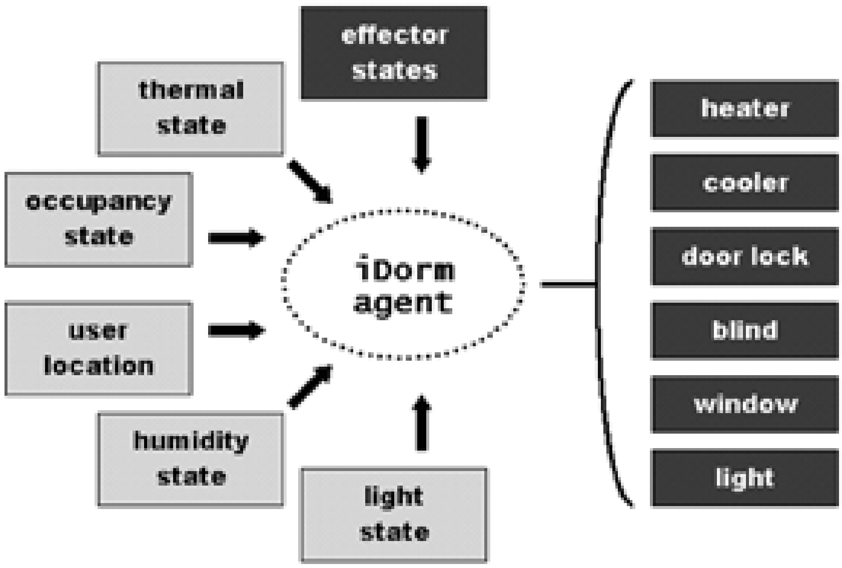

Figure 2. The high-level I/O of the iDorm agent.

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Intelligent robot trends

continued from p. 3

vices such as health care, education, security, space, and undersea exploration and related non-manufacturing areas. Also, a new type of robot is emerging, which may be called a web robot or spider. Although designed for useful searches, they may also be misused.

An example of an educational application is BEST. Seeing a computer algorithm translate into the motion of a robot provides realism and depth of understanding about how patterns and abstraction result in concrete action (seen in Figure 2). Students from the Building Enthusiasm for Science and Technology (BEST) program run the University of Cincinnati Bearcat II robot.[3] On the consumer side, Friendly Robotics[4] (Abiline, Texas) now offers an affordable robot lawn mower, shown in Figure 2. The robotic lawn mower product, the RL500 is fully automatic, operates on rechargeable batteries and costs about $795. More information including a movie are available.[5]

Figure 2. Friendly Robotics affordable lawn mower.

Figure 3. Motoman mixed size/content palletizing workcell.

For an industrial example, mixed size pal-letizing is an interesting application. In a typical distribution center shipments are received and placed in a storage and retrieval system. When a customer's order arrives, the materials are retrieved from storage and palletized for shipment to the customer. A Motoman robotic palletizer (see Figure 3) does this operation automatically.

Trends

- **Many new robots will be invented:** The industrial robot has now reached the age of realism and provides a base for a totally new group of inventions that are built on the robot.
- **Robots will become more numerous:** In 1982, the RIA indicated that 6300 industrial robots were in use in the United States. According to the RIA, more than 100,000 robots were at work in U.S. factories[1] in 2000. Continuing this growth by a factor of 20 in 20 years would give about 2,000,000 in the U.S by 2020.
- **Japan will still lead the world in robotics:** Even though the US market is healthy and growing, there is the fact that the US is still significantly behind Japan in the use of industrial robots, automated guided vehicles and mechatronics.
- **Innovation and cooperation needed:** It appears that most advances in intelligent robots have been "bottom up" applied research. The limitation of this bottom up approach is that only low risk technology will be developed. There is also a need for "top down," high risk, research and development. New ideas need to be tried. Theoretical research and development that can be used by everyone needs to be funded by the government.

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Heterogeneous multi-robot cooperation

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Underwater vehicle navigation

continued from p. 6

translation along Z axis (Tz), rotation around the axis normal to the image plane (R), stretch under conservation of angles and area (S1), and shearing under conservation of area and edge length (S2). Once the projective transformation among the correctly matched coplanar features is estimated—achieved by minimizing an error function through an iterative approach based on gradient descendent—the 3D egomotion information necessary to perform the path alignment is recovered.

Experimental results have been obtained from a video tape from a teleoperated underwater vehicle (the Scorpion-type *ROV-Triton*) that inspected a pipe positioned 130m-deep on the ocean floor. The visual data, acquired with an on-board camera, was recorded in S-VHS. We tested our system on sequences of images from this video tape. The results reported here show the technique can provide information about the kind of movements performed by the vehicle, and that this is useful for achieving some navigation and guidance goals imposed by the inspection task.

The results obtained cannot be quantitatively evaluated because no numerical estimate about the actual motion performed by the vehicle during the acquired sequence is available. However, the quality of the recovered feature matches can be evaluated by observing the matched features superimposed on the respective images (see Figures 1a-b,2a-b). The quality of the estimated egomotion parameters can be evaluated by comparing them with the illustrated motion field (see Figures 1c,2c) and observing where the vanishing point—estimated from the homography coefficients—is located with respect the correspondence vectors. In the case of pure translation, the vanishing point represents the projection on the image plane of the direction along which the observer moves. In the case of pure rotation, it represents the projection in the image plane of the axis of rotation.

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Modular topological mapping and navigation

continued from p. 12

looks for frontal wall segments that are orthogonal to the corridor being traversed.

On the Pioneer-1 AT model, the *Door Detector* processes visual color blob information provided by the underlying vision system, examines the shape of perceived colored objects, and recognizes a closed door by its width and height. When the laser scanner is available, as is the case on the Pioneer-2 DX, a totally different *Door Detector* is used, which analyzes laser scans to extract door signatures. We have recently extended this mapping scheme to the multi-robot case,[9] in which partial topological maps built independently by autonomous robots are matched and correctly combined.

Based on our experience, we make the following observations:

- Behavior-based systems are inherently modular.
- Modularity implies reusability. The system we described in this paper takes code reuse seriously. We are easily able to take a behavior developed for one application and reuse it for a completely different application. Demonstration videos with other systems we have built are available through the web.[10]
- Our systems are extensible. New sensors can be easily incorporated.
- Modular design provides a good basis for coping with heterogeneity.

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Intelligent autonomy

continued from p. 7

lenges. They include:

- State space vs. Information space: these are two algebraically equivalent ways to represent the problem. The information space form seems to offer some advantages. This needs to be investigated.
- Map management: how can maps be managed in such a way that the computational and communication overhead, associated with maintaining and propagating large maps, is alleviated in multiple vehicle SLAM applications?
- Data association: an accurate but practical solution must be found to the problem of feature recognition and correlation.
- Communications: rigorous methods are required to deal with potential rumor propagation problems when maps are passed around communication loops in general multi-vehicle network topologies.

Applications of Decentralized SLAM extend beyond the battlefield.

These include undersea navigation and planetary exploration. Consequently, its challenges should stimulate wide interest within the robotics community.

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Modular behavior-based topological mapping and navigation

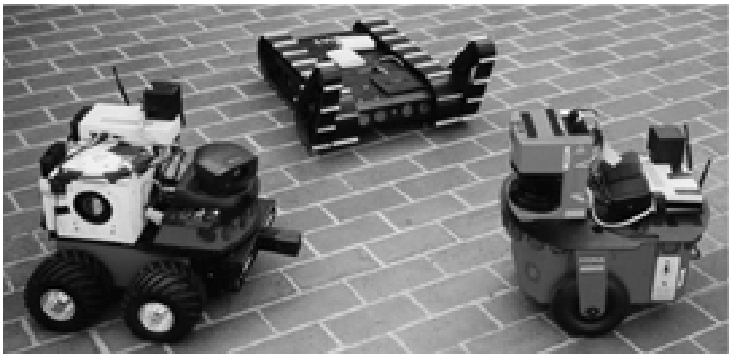

Figure 1. The mobile robot testbed.

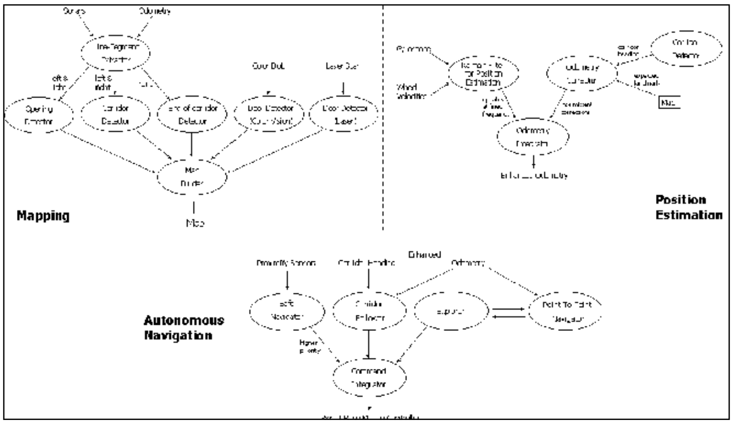

Figure 2. Navigation, mapping and exploration.

Behavior-based systems have become popular as a means of mobile robot control. In a recent paper[1] we described four examples of behavior-based, multi-robot system we constructed over the past two years. These systems are modular, extensible, reusable and heterogeneous, making them useful for a sustained program of research and application. We focus on one of those examples (navigation and mapping) here.

Behavior-based systems have their genesis in the subsumption approach[2] and have been extensively reported in the literature.[3] They have been applied to a diverse collection of tasks such as navigation, terrain mapping, distributed group foraging, etc. We think of behaviors as distributed processes that have direct connections to each other or to the sensors and actuators on the robot. This representation has also been used by others[4,5] with considerable success.

System description

From a hardware point of view, our mobile robots are a heterogeneous group. The Pioneer-1 AT (Figure 1, left) is designed for outdoor applications, the Urban Robot (Figure 1, middle) offers good mobility via tracks and can climb stairs thanks to its actuated arms, and the Pioneer-2 DX (Figure 1, right) is an indoor robot platform with a two-wheel differential drive and a caster. From a control point of view, these robots use a common interface. Lower-level micro-controllers provide a set of commands that allow translational and rotational velocities to be set, and sensory information is updated periodically, both over a serial line.

Our robot-control algorithms are implemented as a set of behaviors[2,6] that are specialized light-weight processes running in parallel. Ports serve as communication channels between behaviors, and their connectivity is defined based on the task. At run-time, a behavior typically completes its sense-decide-act loop as follows. If input ports relevant to the task have not been updated by sensors or other behaviors, it simply suspends execution for a cycle. Alternatively, if some internal timer has expired or new input data is available, it proceeds to execute its computational task, posting the results at the output ports. The particular behavior-based programming language we have used is Ayllu,[7] which is one of the programming tools shipped with the Pioneer robots.

Topological mapping and navigation

As discussed in an earlier paper,[8] we developed an incremental, topological mapping and autonomous navigation scheme geared for time-critical indoor exploration tasks. The aim of our mapping system is to enable users to efficiently acquire an overall view of the main characteristics of the interiors of a building, consisting of basic topological features such as corridors, junctions, and corners. The incremental nature of the approach allows the user to view the most up-to-date map displayed at any time.

The navigation strategy is simple: a robot traverses corridors while avoiding obstacles, turning only when its path is blocked. Like any other behavior in the system, the exploration strategy is independent of the other modules, and can be replaced easily. Figure 2 depicts the behaviors involved in the navigation system and their connections. *Safe Navigator* is responsible for avoiding obstacles based on readings from proximity sensors, i.e. objects too close to the robot cause it to move away from them. Explorer, on the other hand, only cares about successfully following corridors or moving along walls. The *Point-To-Point Navigation* module accomplishes short-lived, open-loop navigation tasks solely based on odometry. The *Command Integrator* gives priority to *Safe Navigator* whenever the latter is active. The *Opening Detector* is designed to watch for discontinuities in the sonar data. The *Corridor Detector* seeks sufficiently long, and overlapping right and left wall segments with approximately matching bearings, and outputs their average heading. The *End-Of-Corridor* detector

continues on p. 11

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