APPENDIX C. SITE REPORTS—EUROPE

Site: ABB Laboratory
Corporate Research Center
Forskargränd 8
SE 72178 Västerås, Sweden
Tel +46-21-32 30 00, Fax: +46-21-32 32 12

Date Visited: April 29, 2005

WTEC Attendees: B. Wilcox (Report author), G. Bekey, V. Kumar, R. Ambrose, Y. T. Chien

Hosts: Chun-Yuan Gu, Program Manager, Mechatronics and Robot Automation, ABB
Corporate Research Center, Email: chun-yuan.gu@se.abb.com
Tomas Lagerberg, Manager, Automation Technologies, ABB Corporate Research Center,
Anders Nylander, President, Business Area Unit for Robotics and Manufacturing of
ABB Automation Technologies

BACKGROUND

The morning session at ABB was led by Program Manager Chun-Yuan Gu (Mechatronics and Robot Automation) and Manager Tomas Lagerberg (Automation Technologies) from the ABB Corporate Research center. In the afternoon session, we were joined by President Anders Nylander of the Business Area Unit for Robotics and Manufacturing of ABB Automation Technologies AB.

ABB employs about 100,000 people—45,000 in power systems (grid control, transformers, high voltage AC and DC transmission up to 800 KV, etc.) and 55,000 people in automation (motors, contactors, soft starters, speed controllers, frequency converters for up to 50 MW machines), instruments for temperature, pressure, pH, etc., and control systems (input/output (I/O), software (SW) for process control).

They showed a demonstration of two robots performing coordinated motion (simulated adhesive bead laydown on bond line), using one controller for the two robots. To specify waypoints, it takes perhaps one hour to define a bond line on a computer-aided design (CAD) part. An important point is that many customers don't have CAD models. For example, automotive manufacturers don't release their CAD models to their piecepart suppliers. Instead they supply a master copy of a part. Small robots are repeatable to within 0.1 mm, and it is possible to get to 0.02 by iterative learning, although this requires substantial thermal stability. Large robots are repeatable to about 0.1 mm.

There are nine research programs at the ABB research center: SW technology, Advanced Industrial Communications, Manufacturing Technology, Power T&D, Mechatronics and Robotics Automation, Nanotechnology Applications, Power Electronics, and Power Device Technology.

ABB does not really do basic research—that is done at universities. ABB collaborates with universities; it has agreements with the Massachusetts Institute of Technology (MIT), Carnegie-Mellon University (CMU), Stanford, Cambridge, Imperial College, and Swiss Federal Institute of Technology (ETH) in Switzerland.

The nine R&D programs represent different areas on the Enterprise/Products/Solutions chart.
The mechatronics and robot automation research effort focuses on advanced robot design and integration.

In 1974, ABB introduced the world’s first microcomputer-controlled electric robot: IRB6. In 1982 they introduced joystick programming of robots. In 1986 they introduced the AC drive on robot motors. In 2002 they were the first to reach a cumulative sales total of 100,000 robots.

They have introduced a product “RobotStudio” simulation tool for easy programming.

At present, the unit cost of hard automation crosses over with robots between manufacturing volumes of 100,000 to 1 million units. With manual labor there is an essentially constant unit cost, independent of the number of units. So there is a “robot zone” where robotics can be competitive with both manual labor and hard automation. The key to future use of robotics is to expand this zone.

Next, the WTEC team met with President Anders Nylander of the ABB Business Area Unit for Robotics and Manufacturing.
There is 5–7% annual growth in robotics worldwide. The automotive industry is the key driver for robotics. The definition of robotics is restricted to systems with five or more degrees of freedom (DOF), so many of the SCARA robots commonly used for electronics assembly do not qualify as robots under this definition. Also, computerized numerical control (CNC) machines (e.g. computerized milling machine, even those with more than five axes) do not qualify as robots. Major markets include foundry operations, spot and arc welding, etc. There has been substantial price erosion in recent years.

They are working on “virtual robot” software, which allows planning, programming, commissioning, operations, and production statistics. The automotive industry wants to use as little space as possible, and robots now are cheaper than hard automation and more flexible. The automotive industry is still relatively labor intensive. It strives for common standards, needing simplicity and reliability.

Next, Christer Norström presented the concept of “Robot Dalen (Valley).” Norström is professor at Mälardalen University, which has 15,000 students, 225 grad students, 57 professors, and $120 million in U.S. research funding per year.

There is a concept from the U.S. called “Triple-Helix” that says there is a need to stimulate BOTH research and business in a healthy business climate. The concept of the Robot Dalen started from industry and research (Mälardalen University and Stockholm are in the same valley). There are 15,000 people in the valley now working in the area of automation. This includes industrial robotics as well as grippers, system integrators, field robotics, robotics for healthcare, and Volvo Heavy Equipment (who, along with Caterpillar and Komatsu are the “Big Three” in worldwide heavy equipment). The Robot Valley concept is to create an efficient system for developing ideas and fostering innovation.

An example is for elder and healthcare—what can we do in rehabilitation? Measuring the degree of rehabilitation is closely related to athletic training equipment. In Sweden there is a fundamental economic problem that all hospitals are under government control, and they do collective procurement. So there is no way to get into the market in an incremental way.

Another example is education in the widest sense. The Lego robotics competition is an example that requires teachers to take robotics classes.

Support for innovation is difficult. Their goal is to have 40 start-up companies per year founded by students. Industrial robots are now a commodity product with high volume and low margins. Agricultural robots are just taking off. Healthcare robots are in their infancy. Every president of a company wants to move all manufacturing to a “low-cost labor” country. But the Robot Valley team has done a survey and found that 9 of 14 will have a better return on investment if they “robotize” rather than moving. The Robot Valley team helps with competence - they induce students in the universities in the valley to take a course in automation in their senior year. They establish mentor groups, with two students, a product leader, a professor, and a system integrator. They are doing this now with 50 companies within a 70 km radius.

The key challenges they face are:

- It is perceived as too expensive to install a robot (people in companies should be able to install it themselves)
- The time it takes to change products is too long
- The utilization of robots is too low
- The environment is not as deterministic as assumed for most robots
- There is little support for human-robot cohabitation
- Management fears “what if they buy a robot and it doesn’t work?” How can they intervene so that work continues even though a robot is not working? How can they do “incremental robotization?”

A study was recently done in Sweden that shows that big factories such as Volvo are at the state-of-the-art (SOA). But small companies are not SOA, and in many cases are far behind. But the large companies depend on the small feeder companies.
Site: Charite Hospital  
Campus Virchow-Klinikum  
Clinic for Maxillo Facial Surgery-Clinical Navigation and Robotics  
Berlin, Germany

Date Visited: April 28, 2005

WTEC Attendees: R. Ambrose (Report author), M. Dastoor, Y.T. Chien, B. Wilcox, D. Lavery

Hosts: Prof. Tim C. Lüth, Email: tim.lueth@ipk.fraunhofer.de  
Juergen Bier, Email: juergen.bier@charite.de

BACKGROUND FROM REMARKS BY PROF LÜTH

We again met up with Prof. Lüth at Charite, where we were initially shown the applications of his research at Fraunhofer Institute, Production Systems and Design Technology (IPK). This dual role for Prof. Lüth is an excellent example for other countries wanting to find a path for integrating technology and research into applications. Prof. Lüth’s involvement at both sites is deep and has yielded great results.

Lab tours

The facility included a wide mix of small machine shops and integration areas, mixed with facilities for clinical trials, teaching hospital theaters, and full-time surgical suites. This vertical integration of the research, founded at IPK, is not matched in the U.S.

The study team was taken through a series of labs with multiple generations of navigation systems developed in-house. The latest generation has reduced the required inter-ocular baseline to a small distance (~0.4 m) and is mounted on a small roller mount that takes up only a small amount of floor space. The optical markers are significantly smaller than their competition, are tracked with a well-tested software product now in wide distribution.

Figure C.3. NC Machining Center in prototyping lab.
Figure C.4. Second generation optical tracking system (over David Lavery’s head) (left), first generation optical tracking system (right).

Figure C.5. Third generation optical tracking and cranial mounts (left), Dr. Lüth demonstrates use of registration software (right).

Figure C.6. Registration probe (left), registration trackers on dental mount (right).
Figure C.7. Lower extremity fixture and motion tracking system.

Figure C.8. Close-up of registration software interface.
C. Site Reports—Europe

Site: CNES  
Centre National d’Etudes Spatiales de Toulouse  
18 Avenue Edouard Belin  
31 401 Toulouse, Cedex 4, France

Date Visited: April 25, 2005

WTEC Attendees: B. Wilcox (Report author), R. Ambrose, Y. T. Chien, M. Dastoor

Hosts:  
Michel Maurette, Robotics expert, Laboratory Centre Spatial de Toulouse,  
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Email: michel.maurette@cnes.fr  
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BACKGROUND

On the way from the visitor center to the lab, we were taken by Michel Maurette to a Mars-like test area, about 30 x 50 m. It is in a shallow depression so that mast cameras don't see other terrain outside the nominal test area. There is a small lab building nearby for test support. There were no tests in progress at that time. They have 10 cm ground truth topography for this site.

From there we went to the robotics lab. We first visited a room in the back with a very complete and sophisticated stereo calibration and test area, including stereo camera heads being developed for flight. There was very careful attention to maintaining mechanical rigidity and alignment during the fabrication of these heads. Originally, they started with 20 cm stereo camera separation, but now are using 12 cm separation, and may go down to 10 cm as camera resolution continues to improve. They are using the same 1024 x 1024 pixel cameras that are used on the Rosetta comet mission (and on the Space Station). They are using a “stacked chip” packaging technology they have qualified thermally from -120°C to +20°C and also through the Ariane-5 launch vibration spectrum. On one side of the room is a large collimator used to project identical spots as seen from infinity into both cameras of the stereo head for calibration. On the other side of the lab is a ~3 x 4 meter test area with brick-red gravel glued to regular geometric shapes (e.g. rectangular and triangular prisms) to validate the performance of stereo cameras mounted on motion stage. They calibrate each camera to a fifth of a pixel, and use a ~50 x 50 lookup table plus interpolation to do ortho-rectification. They expect to do visual odometry every 10 to 50 cm of vehicle motion, and to perform stereo correlation and path planning every two meters.

Next, we moved to the adjacent software development area, where we were shown a simulation of a Mars rover in computer-generated terrain. The claim is that the algorithm they are developing is superior to the Mars Exploration Rover (MER) in that it plans paths that are more complex than simple arcs, and this is needed if the terrain is very difficult. In the example shown, as the terrain map is built up using simulated stereo data, it becomes clear that there is no passable way out, it is only possible after a complex path is planned out through the last possible opening. At the end, new stereo range data shows (as the vehicle approaches it) that the final exit is not passable.

All software is in ANSI “C” and ground support is in Motif/Open-GL (X11). They are transitioning to the compact-peripheral component interface (PCI) bus on their research rover Illustrateur Autonome de Robotique mobile pour l’Exploration Spatiale (IARES) (most existing equipment is VME). All code works on Intel or PowerPC processors with same source code.

There was much discussion around a Russian rover chassis used in IARES that has many degrees of freedom (DOF). The chassis has six-wheel drive, with turning cylinders on the undercarriage to prevent high-centering. It has six-wheel drive and steering, two speeds with a brake on each, and has an “inchworm” peristaltic mode for use in very soft terrain. It takes 1 W to release the brakes.
We were joined by Guy Laborde, the “Chef de Service of the Bancs and Simulateurs Systeme.” There was some discussion of the proposed European Space Agency (ESA) Exo-Mars mission, planned for 2011 or 2013. Pre-phase A for that mission is done, and it is now in Phase B. The rover under consideration is a 6-wheel machine with single body (as driven mostly by the mass limitation), similar to the rocker bogie used for Sojourner and MER. Stereo vision is the baseline for hazard avoidance, since it is light and involves no moving parts. A laser rangefinder has also been studied. The planned landing will occur within ±45 degrees of latitude and below 2 km (Mars Orbital Laser Altimeter (MOLA)-grid) altitude (as generally required for parachute-assisted landing).

The test vehicle IARES has a passive roll axis front and back, and a powered roll on the center cab. The no-load speed is 50 cm/s in high gear, 10 cm/s in low gear. Typical loaded speeds are half that.

Their view is that CNES will develop the software, and the Russians will participate in developing the hardware. CNES has made extensive use of the Marsokhod rovers in the past. In particular, the Russians (VNIItransmash) have optimized the kinematics for the Exo-Mars mission chassis.

For hazard avoidance, the threshold to declare an object an obstacle is the step height based on the footprint of wheel and slope for axle (in many different rover positions)—they save the worst number. The path planner is not like MER in that the planner uses a two-stage pyramidal algorithm in which the first step consists of an “A” algorithm, the result of which is used for A* optimal path finding. The previous perceptions are merged with the current one and used for path planning. Their inertial measurement unit (IMU) is a concern because its mass is 10 kg, and it requires frequent recalibrations. They believe that visual odometry is better. They currently do sun sensing on every stereo cycle. They are considering use of landmarks as well as regular localization from orbiter.

There were a few people in the lab doing software development. There was a hardware development area nearby, including a small machine shop.
Site: Cybernétix
Offshore Division
Technopole de Chateau-Gombert, BP 94
13382 Marseille Cedex 13, France
http://www.cybernétix.fr

Date Visited: April 27, 2005


Hosts: Peter Weiss, Coordinator of European Programs, Offshore Branch,
Email: peter.weiss@cybernétix.fr

BACKGROUND

Cybernétix is a small company specializing in robotics and automation systems. Cybernétix has programs that focus on:

- Increasing productivity of production lines
- Improving product quality
- Replacing human intervention for difficult, dangerous, painful and unrewarding tasks

Cybernétix optimizes the design and the manufacturing of products, processes, equipment and systems through a global approach of automation and advanced robotics, and studies project feasibility and develops prototypes.

The Offshore Branch is focused on systems for ships and underwater applications including inspection, maintenance, and repair of deepwater facilities.

Overview of the Visit

Our visit to Cybernétix was hosted by Peter Weiss, the coordinator of European Programs, Offshore Branch. The visit included an overview of programs and a visit to laboratories and instrumentation at the Marseille laboratory.

OVERVIEW OF CURRENT ROBOTICS RESEARCH

Cybernétix activities in technology development include four major areas:

Deepwater Intervention

Recent and current programs include: deepwater intervention, inspection and maintenance, construction assistance, and monitoring.

Crawlers

SPIDER is a crawler for deep and shallow deployment with particular application to pipeline inspection and surveys. The adjustable weight and configuration makes it suitable for shallow, high current areas where traditional remotely operated vehicles (ROVs) are difficult to implement. The vehicle is 4.3 meters in length, 1.7 meters in width, and 2.3 meters in height, and weighs 1,800 kg with a remote power supply. The operating depth extends to 1,500 meters. The crawler supports sensor systems for visual, sonar and other inspections, and includes a telescopical zoom with pan and tilt camera.
The PMS Pilot mining system for the recovery of polymetallic nodules works in waters 6,000 meters deep. The remote operated crawler is equipped with a pumping system to collect the nodules at the seabed, crush them and send the mixture to the surface. The PMS was developed in cooperation with the China Institute of Mining Systems (CIMR).

**AUVs**

SWIMMER is a hybrid system concept that includes an autonomous carrier vehicle, which is able to transport a standard ROV to a subsea docking station. Once docked to the station, the ROV can be controlled from the surface. The SWIMMER vehicle is 6.1 meters by 2.5 meters by 2.5 meters, and weighs 4,785 kg. The SWIMMER shuttle is operated like an AUV and moves toward a predefined approach point using an acoustic telemetry link to monitor and control the vehicle. The shuttle stabilizes 20–30 meters above the target location, and vertically lands onto the docking station with the help of a short-range positioning system. The shuttle locks onto the docking station and connectors are mated enabling the ROV to be powered and controlled through the umbilical. The ROV is then released from the shuttle and operated from the surface as an ROV.
ALIVE is an intervention autonomous underwater vehicle (AUV) able to execute telemanipulation tasks on subsea structures. This project is conducted jointly with Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER) and Heriot-Watt University.

Typical applications of the ALIVE vehicle will include:

- Carrying out emergency inspection/intervention in case of environmental disaster (e.g. sunk tanker)
- Helping in rescue and salvage operations where the vehicle could be mobilized extremely rapidly (e.g. by helicopter) as opposed to divers or ROVs which need surface support
- Contributing to cleaning operations such as debris removal from protected sites without having to mobilize costly diving vessels where scuba diving is not possible (below 50 m)
- Carrying out site investigation in areas suspected to be polluted by radioactive materials or chemical weapons (where there is high risk for human divers)
- Recovering seabed samples to control sediment contents without having to operate costly intervention spreads that limit the duration of the campaign
- Operating subsea infrastructures such as a benthic station (to download data for example) or an oil wellhead (to actuate process valves) in a very cost-effective manner and with reduced impact on the environment (smaller surface vessel is used if any, and therefore provides reduced fuel consumption and lower pollution risk)
The ALIVE vehicle is 4 meters long, 2.2 meters wide, and 1.6 meters high, and weighs 3,500 kilograms. The propulsion is provided by five electrical thrusters. The navigation sensors include an inertial navigation system and Doppler velocity log for autonomous navigation and dynamic stabilization. A global positioning system (GPS) is linked to surface long base line (LBL) for underwater positioning. A doppler profiler is used for target approach. The SAMM seven degree-of-freedom (DOF) manipulator includes two hydraulic grippers for docking. The manipulator is preprogrammed for manipulation tasks and operated using a supervisory control mode during missions. Communication is provided by an Ethernet umbilical plus on-deck and high-reliability low data rate (100 bps) bi-directional acoustic communication for mission supervision. A high data rate (5 kbps) acoustic communication link is available for uploading compressed sonar/video images during manipulation tasks. The power is provided by pressure-balanced lead-acid batteries with 240 VDC, 40 kWh for thrusters and hydraulic power, and 24 VDC, 4 kWh for instruments. It is possible for a typical mission to last seven hours.

ROVs

JUNIOR is a deepwater compact observation ROV rated to a 3,000 meter depth and dynamic positioning (DP) station-keeping capability. The small size of this ROV (0.65 meters by 0.45 meters by 0.33 meters) makes it convenient to deploy and maneuver. The principal application is to provide an observational capability for inspection or for monitoring of another working ROV.
Inspection and Maintenance

These programs include:

- MHC (Magnetic Hull Crawler) (for Inspection) is a robot that attaches magnetically to a ship’s hull and moves over the surface performing inspections.

![Image of MHC](image1.jpg)

Figure C.19. MHC for underwater non-destructive testing (NDT) and visual inspections.

- ICARE is a remotely operated anchor chain cleaning and inspection system.

Construction Assistance

These programs include:

- Magnetic Hull Crawler (MHC) (for painting and cleaning) is a version of the magnetic attachment system that supports abrasive cleaning and painting.

![Image of MHC](image2.jpg)

Figure C.20. MHC for UHP cleaning of ship hulls.  Figure C.21. MHC for hull painting applications.

- SAPPS is a deepwater pipeline flushing, pigging, and hydrotesting system.

Monitoring

These programs include:

Girassol is a subsea monitoring and data collection system, including stress and strain measurements, riser tower dynamic behavior recording, and temperature recording.
Site:

**D. Site Reports—Europe**

**Site:**

DLR German Aerospace Center
Deutsches Zentrum für Luft
Institute of Robotics and Mechatronics
Munich, Germany

**Date Visited:** April 27, 2005

**WTEC Attendees:** R. Ambrose (Report author), Y.T. Chien, B. Wilcox, D. Lavery, G. Bekey, V. Kumar

**Hosts:** Prof. Gerd Hirzinger, Tel: +49-8153-28-2401, Fax: +49-8153-28-1134, Email: Gerd.Hirzinger@dlr.de

**BACKGROUND FROM REMARKS BY PROF HIRZINGER**

Prof. Hirzinger gave an overview of the Deutsches Zentrum für Luft (DLR) history and future plans for space robotics. The depth and breadth, quantity and quality of the work are first class. His organization has over 150 people, with a unifying basis:

*Multi disciplinary virtual design, computer aided optimization and realization of mechatronic systems and man-machine interfaces (towards intelligent mechanisms, which react with their environment and model it).*

Throughout the work, there is attention to the close integration of mechatronics, merging mechanical and electrical engineering design. This is a holistic design and concurrent engineering approach.

**PRIOR WORK**

**Rotex**

The DLR’s Rotex experiment was a major landmark in space robotics. The flight experiment positioned a small, light and fine arm in an intravehicular activity (IVA) experimental rack aboard the Space Shuttle. This experiment tested a mix of control modes, and demonstrated dexterous manipulation in zero gravity. Particulars of the experiment are:

- Flew in 1993
- Demonstrated ground control
- Flight led to the space ball product
- Five to seven second time delays
- Predictive simulation demonstrated to compensate for delay
- Shared control

The user told it to rotate, the machine felt the screw, and it advanced in helix autonomously.

**Getex**

DLR’s participation in Japan’s ETS VII free-flying space robot included advanced forms of teleprogramming and dynamic interaction experiments between the robot and carrier satellite.

**OLEV (ORBITAL LIFE EXTENSION VEHICLE) OR CONEEXPRESS**

A flight demonstration is now being proposed to rendezvous with a satellite and capture it by means of inserting a specialized end-effector into the nozzle and rigidizing. The overall approach is similar to the Defense Advanced Research Projects Agency (DARPA) Spacecraft for the Unmanned Modification of
Orbits (SUMO) project. A technology presentation was demonstrated the approach. Particulars of the proposed system include:

- Model-based servoing
- One camera feature matching for auto capture, six degrees of freedom (DOF)
- Three dimensional reconstruction with Wei, 1997, using radial basis functions
- Orbital recovery, Dutch space, Kaiser Threde project aiming at the “business case” of servicing in space
- In Phase B

![Industrial robot integrated as 0 g emulation for nozzle capture experiment.](image)

**TECSAS**

DLR’s seven DOF free-flying arm on a carrier satellite is supposed to approach a target satellite and grasp it either autonomously or via telepresence, perform a number of motions in compound state and finally deorbit the target.

DLR’s work in dexterous limbs is particularly excellent. The lab has a long evolution of systems, as is almost always the case to achieve such depth. Three generations of hands and arms have been developed, with the following particulars:

**Hands**

- I, 1998, tendons,
- II, 2002, 13 DOF with good thumb, only 12 lines coming out
- 3 kg finger tip grasp
- 2005 DLR/HIT hand, a slightly simplified version of Hand II (1 kg fingertip) now to be commercialized by the company Schunk

**Arms**

- LWR II 1999 17 kg
- LWR III 2003 13 kg/20 kg load capability, high motion speed
- Dual access to joint avionics with end caps for maintenance
- Kuka will fabricate the arm
Prof. Hirzinger told us that the next generation will be an integrated forearm/hand with a modular upper arm. Motor design is a key part of this work, optimized for very high dynamics, but with low speed and single pole windings. Hand design has focused on fast motion, and has gone away from tendons and back to double differential bevel gears. The first hand with spindle cables was very high maintenance. Each finger has a six-axis load cell on the tip. DLR has formed an agreement with Schunk, which will come out with 20 new hands, at a cost of maybe €25,000.
ROKVISS

Robots have been given a too-high burden for manned space flight. DLR was able to prove its two joints would not be a thermal problem. Proved event upset proof design. The system has two black and white cameras. On reboost it was on the wrong side, and an antenna was blocked temporarily. This and other problems were overcome with extravehicular activity (EVA). Particulars include:

Tasks

• Part mating
• Contour following
• Experiments with artificial delay
• Educational program with students commuting fly over and aiming camera at the city

The lab visit ended with a demonstration of mobile manipulation. An earlier version of the lightweight arm and hand were mounted on a mobile, wheeled base. The robot positioned itself in front of a door, and placed its hand on the door handle. The handle was a bar style handle, where the lever must be rotated from a horizontal axis downward to the vertical axis. As the arm pushed on the handle, the force control reacted to
the rotation, finding the axis of rotation and complying. This concluded a set of six real-time demonstrations, which is unusual. The fact that the six systems were of such a high caliber should be noted.

Figure C.28. Dexterous arm on mobile base, opening door (left), robot passing through doorway (right).
Site: EPFL
École Polytechnique Fédérale de Lausanne
Swiss Federal Polytechnic University at Lausanne
http://www.epfl.ch

Date Visited: April 26, 2005

WTEC Attendees: Vijay Kumar (Report author), G. Bekey

Hosts: Francesco Mondada, Email: francesco.mondada@epfl.ch
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OVERVIEW

The activity in mobile robotics at École Polytechnique Fédérale de Lausanne (EPFL) was started by Professor Jean-Daniel Nicoud. He was a pioneer in robotics, the developer of the Khepera robot and one of the founders of K-Team, the spin-off company that manufactures the Khepera and the larger Koala robots. The robotics effort at EPFL spans across three schools: Engineering Sciences, Information Sciences, and Life Sciences and involves four different laboratories, the first three in engineering sciences and the fourth in computer science.

Labs in the School of Engineering Science—These include the Laboratory of Intelligent Systems of Prof. Dario Floreano, the Laboratory of Autonomous Systems of Prof. Roland Siegwart and Dr. Aude Billard, and the Laboratory of Robotic Systems of Prof. Reymond Clavel.

Labs in the School of Informatics—These labs include the Non-linear Complex Systems Laboratory where Dr. Alcherio Martinoli is addressing sensor networks and collective robotics, and the Laboratory of Logic Systems where Dr. Auke Ijspeert carries out work on biologically inspired robots.

Labs in the School of Science—These include laboratories on neuroscience and genetics, brain prosthetics, and neuromuscular coordination. The effort in life sciences involves research in neural basis of sensorimotor coordination and applications to brain prosthetics, and as such, is not directly integrated with the other groups, although there are plans for integration in the future. A strength in this area is Henry Markram, who has many papers in *Science* and *Nature* on new models for synaptic behavior. This work, in particular, suggests future research directions in robotics and neural networks (instead of connectionist models).

Lab for Intelligent Systems
Director: Prof. Dario Floreano

The major goal of this lab is to develop systems that successfully mimic the ability of biological systems to self-organize and adapt to changing environments. The lab has thrusts in bio-inspired robotics, neuro-morphic control, and adaptive swarm robotics. Prof. Floreano is highly regarded for his work in evolutionary robotics. His book in this field is excellent (Nolfi and Floreano, 2004). In this lab we saw truly remarkable lightweight aircraft, weighing as little as 9 grams (including two 1 g cameras). The wings are covered with what appears to be a thin vinyl film. We saw a video of the aircraft in motion (also shown at ICRA 2005), showing that the vehicles had obstacle avoidance ability and turned as they approached the walls during indoor flight. An experimentation room contained a number of SwarmBots, mobile robots equipped with a grappling arm, developed jointly with Marco Dorigo in Belgium and other labs under an EU grant. The robots wander until they approach one another, and then one of them extends an arm to connect to a rim on the other, ultimately creating a chain or a cluster of robots. Another research activity concerns the evolution of cooperation and division of labor with sugar-cube robots that are required to cooperate in order to cluster objects of different sizes at a station (bottom image of Fig. C.29).
Lab for Autonomous Systems
Director: Prof. Roland Siegwart; Assistant Prof: Aude Billard; Senior Researcher: Francesco Mondada

Prof. Siegwart is primarily interested in mechatronics: the design and fabrication of robots capable of operating in uncertain dynamic environments, and software for mapping and localization. His lab has been involved in the design and fabrication of a number of robots. One of them is a very small (a cube approximately 2 cm on a side) autonomous vehicle named “Alice.” This robot is used in a number of projects at EPFL, including a Robocup team in this lab. Alice communicates with other robots by local infrared (IR); it also has radio frequency (RF) communication with a range of 6 m. The battery life lasts up to 10 hours.

One of the most interesting projects we saw in this lab concerned mixed societies of live insects (cockroaches) and small robots (InsBots) of approximately the size of a cockroach, but with a completely different body shape (basically a parallelopiped). The robots are sprayed with a chemical so that they approximate the smell of the insects. They are then accepted by the cockroach society and can influence the society behavior.

We also saw an “intelligent car,” related to the German autonomous car project initiated by E. Dickmanns.
The humanoid group is directed by Aude Billard, who is a Swiss National Science Foundation (SNF)-supported assistant professor. It is also part of the Autonomous Systems Lab. Her focus is on learning by imitation.

Aude Billard was a PhD student of Jean-Daniel Nicoud. Her lab concentrates on robot learning by imitation and other aspects of human-robot interaction. Several of the robots, developed by her several years ago, are dolls about 2 ft in height named Robota. The dolls are equipped with vision and movable arms and legs, which they use to attempt to follow the movements of a teacher. She also has a larger humanoid robot. These robots are intended for educational use with children as well as for therapeutic applications with disabled children.

Laboratory of Robotic Systems—Director: Prof. Raymond Clavel

Prof. Clavel is a highly respected investigator who has published extensively with patents on parallel mechanisms (see below). Unfortunately, because of time constraints, we were not able to speak to him or his co-workers.
Laboratory of Non-linear Complex Systems, Group of Sensor Networks and Robotics  
**Director: Alcherio Martinoli**

Dr. Martinoli’s interests are in sensor networks and swarm robotics. The students in this lab are involved in a number of interesting projects. A swarm project involved a large number (perhaps 20 of the small Alice robots developed at EPFL in Siegwart’s lab), moving randomly in a space that also included 10 or 12 uniformly spaced barriers. When a robot reached a barrier it would follow it to the end, and then move randomly. The study concerned the relation between robot parameters and their ability to find and follow all the barriers in the field while performing inspection. He was interested in bio-inspired behaviors in swarming.

Laboratory of Logic Systems, Bio-inspired Robotics  
**Group Director: Auke Ijspeert**

Dr. Ijspeert is a Swiss National Science Foundation assistant professor with interests in biologically inspired robotics, at the intersection between computational neuroscience, nonlinear dynamical systems, and adaptive algorithms (optimization and learning algorithms). His focus is on locomotion of modular robots. Unfortunately because of time constraints, we could not visit his lab.
TECHNOLOGY TRANSFER

EPFL has an excellent track record of technology transfer with six successful spin-offs in robotics-related fields over the last ten years. We visited two of the six spin-offs, both addressing mobile robot applications. The first, K-Team, is catering to the needs of the research community and universities, and develops small robots for cooperative robotics and swarm applications. The second, Bluebotics, is developing navigation technology for service robotics applications.

We also saw the products of another spin-off, Cyberbotics, which provides simulation environments for mobile robotics. Their product Webots 4 allows the user to rapidly model, program and simulate mobile robots with physically correct dynamics. To support mobile robotics, they provide libraries of actuators and sensors, the infrastructure to simulate communication, and thus the tools to simulate multiagent systems. Alcherio Martinoli's group uses this software to simulate controllers for automated cars (for example, lane change maneuvers).

EPFL policies appear to be more liberal, faculty friendly, and supportive of technology transfer and new ventures in many ways than other laboratories we visited in Switzerland and Germany.

1. They have a facility on campus to incubate new ventures. Although the rent for this space appears to be higher than what is available off campus, it has the benefit of being close to EPFL labs allowing collaborations during the development of the spin-off.
2. EPFL keeps a much smaller fraction of the royalties or the equity in start-ups compared to U.S. universities. Usually this figure is less than 10%.
3. The overhead rate on grants from industry is usually between 6% and 26%.

REFERENCES

Site: ETH  
Swiss Federal Institute of Technology, Zürich  
Eidgenössische Technische Hochschule (ETH)  
Institute for Robotics and Intelligent Systems (IRIS)  
Rämistrasse 101  
CH-8092 Zürich, Switzerland

Date Visited: April 25, 2005

WTEC Attendees: V. Kumar (Report author), G. Bekey

Hosts: Professor Bradley Nelson, Robotics and Intelligent Systems, Director, IRIS,  
Tel: +41 1 632 55 29, Email: bnelson@ethz.ch

BACKGROUND

The Institution

Eidgenössische Technische Hochschule (ETH) was founded in 1855. It is considered one of the 10 strongest universities in engineering in the world. Twenty-one ETH professors have received Nobel Prizes, including Einstein and Rontgen (the discoverer of X-rays). The Zürich campus has 330 professors, divided among 17 departments. It has a total of about 12,000 students (including about 2,000 graduate students); about 500 complete their doctoral thesis each year. An MS program is now being started. The Institute for Robotics and Intelligent Systems (IRIS) is in the Mechanical Engineering and Mechatronics Dept.

IRIS is directed by Prof. Brad Nelson who was recruited from the University of Minnesota over two years ago. As typical in European universities, Brad is only professor in the Institute, and he directs a total staff of 18, including a number of researchers, engineers and a staff person. He received a PhD from Carnegie-Mellon University (CMU) in 1995. He has a very strong research program mainly concerned with microrobotics, biomicrorobotics and nanorobotics.

The IRIS program is divided into three areas:

1. Teaching
2. Microrobotics
3. Nanorobotics

Education

The teaching program currently includes three courses:

1. Intro to robotics and mechatronics (BS level)  
   How to control an arm, read encoders, etc. The course is hands-on; students construct a two degree-of-freedom (DOF) manipulator.
2. Theory of robots and mechatronics  
   This is a pretty standard course.
3. Advanced robotics and mechatronics  
   Competition with mobile robots, emphasizing problem solving with hardware and software. They developed their own mobile platform, but also evaluate ActivMedia and Evolution Robotics.
Microrobotics and Bionmicrorobotics

This thrust focuses on developing intelligent machines that operate at the micron and nanometer length scales. Examples of research projects are briefly described.

Microrobotics for handling biological cells involves the use of vision-based manipulation augmented by force sensing and the development of a microelectromechanical systems (MEMS)-based multi-axis force sensor. The force sensor (8 kHz bandwidth, 1 μN accuracy, 1 μN resolution) is unparalleled. An example of a driving application is the study of embryo properties by biologists, and in particular, the mechanical characterization of embryo membranes.

Figure C.35. A probe station with two micromanipulators and a microscope for biological cell handling.

Another project involves the study of fruit flies and the mechanics of flight. Dr. Nelson works with biologists interested in flight muscles of insects, and performs experiments with fruit flies, whose wings beat at 200 Hz. They use MEMS sensors attached directly to the fly’s muscles. The fly is approximately 3 mm in length, and wing forces are around 35 μN with a 10 μN weight.

Figure C.36. Investigation of the mechanical properties of the cell embryo.

Dr. Nelson is interested in microrobots implanted in the body (e.g., floating in the bloodstream). His lab has developed methods for magnetic steering of microrobots using external power. The microrobots they use are 0.8 mm (800 microns) in length, microassembled. They are exploring ultrasonic sensing for localization of microrobots in the bloodstream.
A second area of work is nanorobotics. The basic goal is to move microrobot research to the nanometer scale. Dr. Nelson and his co-workers are interested in building actuators and sensors in the range of 1–100 nm. They have active collaborations with the FIRST Center for Micro- and Nanoscience and the Paul Scherrer Institute. The work includes fabrication, control and characterization of telescoping multiwall nanotubes, the study of field emission of telescoping carbon nanotubes (CNTs), and the dielectrophoretic nanoassembly of nanotubes onto nanoelectrodes.

A particularly impressive project involves the fabrication of nanocoils made of silicon 30 microns long, 20 nm thick. These nanocoils have a little more than 0.02 N/m stiffness for four to five turns (compared to 1 N/m stiffness for a silicon tip).

Dr. Nelson’s believes the challenges in this area are truly robotics (and not physics- and chemistry-based) problems. Much of the lab’s interests and goals can be viewed as motion planning, integration from multiple sensors, and controlling motion in high-dimensional, unstructured environments.

The Academic Environment

When Dr. Nelson arrived at ETH he was given a start-up package of about $1.5 million and 7½ positions funded by the university (including his own). In addition he receives about 100,000 Swiss Francs annually (about $90,000) for expenses such as travel and supplies. He also has research support from the European Community and from the Swiss National Science Foundation. Salary increases for professors are uniform and independent of performance. If a professor gets industrial support, the university matches it.

The teaching load is very light: a professor only teaches about 2 to 2½ hours per week.

In the introductory course, for example, Dr. Nelson only gives the opening lecture; his assistants do the rest. There is very little pressure on the students. They have no homework or exams. However, each student is given an oral exam at the end of the semester. The students perform very well on these exams because they are highly self-motivated and do not depend on external pressure to study. However, they are not used to the U.S.-style lab courses that require much more work.
Technology Transfer

The group is actively engaged in protecting intellectual property and filing for patents. They are careful about publishing before filing for patents. (Unlike the U.S., researchers do not have a year to file for a patent following disclosure). The patents are owned by ETH if they pay for it, but the researchers can pay for the patenting process and own it.

Dr. Nelson has an extremely talented group, some of whom are U.S. graduate students. In fact, he had an outstanding graduate student at Minnesota who later worked at Honeywell, then could not get a visa to return to the U.S. following a visit to India. That student is now pursuing a PhD at ETH—a big loss for the U.S.
C. Site Reports—Europe

Site: Fraunhofer Institute – Production Systems and Design Technology
Fraunhofer Institut Produktionsanlagen und Konstruktionstechnik (IPK)
Pascalstrasse 8-9, Berlin, Germany

Date Visited: April 28, 2005

WTEC Attendees: R. Ambrose (Report author), Y.T. Chien, B. Wilcox, D. Lavery

Hosts: Professor Dr. Tim Lüth, Tel: +49 (0) 30/3 90 06-120, Email: tim.lueth@ipk.fraunhofer.de
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BACKGROUND FROM REMARKS BY PROF LÜTH

Dr. Lüth gave the group an overview of the Fraunhofer Institute’s operations and his personal background. The Fraunhofer Institutes are intended to complement the basic research underway at the Max Planck institutes. As such, they receive about 25% of their funding from corporate sponsors. The Berlin institute is organized into four groups: Production Systems, Automation Technology, Virtual Product Creation, and the Medical Technology group led by Dr. Lüth. The Automation Technology group built the control system for the Rotex Experiment (described in the DLR site report). The Virtual Products group has a visualization center like the U.S. “caves.”

MEDICAL TECHNOLOGIES

The Medical Group was founded in 1986. It has 441 employees, with an operating budget of about €23 million each year. Within this, the Medical Devices team has 25 people, focused on the goal of providing the appropriate functionalities that utilize a common, unchanged sequence of surgical operations. Towards this end, the team has worked towards assistive rather than surrogate systems.

The key technologies being developed by this team are navigation, robot design/mechanisms, and navigated control. The term “navigation” was used in a similar way to the term “real-time registration,” providing high-bandwidth data to localize a tool with respect to anatomy, in a coordinate frame that is shared by a 3D model. The 3D model is produced using X-ray or magnetic resonance imaging (MRI) methods, including a fixture that has an attachment for a registration marker.

A unique approach developed by Lüth’s group shares control of the tissue removal tool between human and robot. The early work had failed to match the speed goals for surgeons, having used an industrial robot with too low a speed and too much inertia (Mitsubishi PA-10 seen in the lab). A more successful approach has been to allow the human to hold the tool, but only enable its high-speed cutting motor when it is positioned in the 3D zone that has been pre-planned for removal. As the tool leaves this region, the motor is stopped.

Notes for Specific Surgeries

Ear example

- Add facial prosthesis ear
- Install mounts below skin
  - Drill and tap
- Place ear to ±1 mm
- Surgeon moves arm, pushed by hand
- ISO 9000 certified
- World’s first robot for head surgery
- Developed for a non-cooperative use (surgeon)
Spine surgery
- Decompression of the vertebrae
- Uses Mitsubishi PA-10
- Arm found to be too slow, needs more power, but that is dangerous
- New idea
  - Replace arm, use instruments on surgeon’s arm
  - Power off tool if in bad location

Multi-step Operations
- Photography
- Place markers
- Redundant calibrations
- Displays
  - Glasses cause fatigue (change in focus from hand distance)
  - Went to 4" displays
  - Audio cues as tool approaches dangers
  - Animated tool changes color (green is good)

PHOTOS FROM LAB TOUR

Figure C.38. Integrated manufacturing cell with Kuka robots and NC tools (left), parallel mechanism and integrated seat (right).

Figure C.39. Human motion augmentation system for lifting heavy payloads (left), human offloading and tracking system for motion studies (right).
Figure C.40. Multiple generations of intelligent registration equipment (left), remote center mechanism for 3D imaging (right).
Site: Università di Genova  
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BACKGROUND

The University of Genova is one of the most active institutions in robotics research in Italy, and one of the two Italian universities that the assessment panel chose to visit. Research activities are primarily concentrated in the Department of Communication, Computer and System Sciences (DIST). Our visit to the institutions consisted of touring five individual laboratories, each led by a faculty member.

Research Activities at University of Genova DIST

The Laboratory for Integrated Advanced Robotics (LIRA) led by Professor Giulio Sandini

The laboratory has several projects going on; three will be described here. The first project studies a robotic arm equipped with a five-finger robotic hand and two robotic eyes. The arm has seven degrees of freedom (DOF), and the eyes have eight. The primary purpose of the project is to study the sensor-motor control scheme of human beings and to implement it on the robotic arm. Questions like, how a human handles the object when he/she sees it, and how a newborn learns to grasp objects, etc., are studied. Research topics also include grasping according to the shape and function of objects. The project is quite new and is sponsored by the Toyota Motor Company of Japan. During the visit, we were not allowed to take pictures. According to the host, an identical robot arm has been installed at a Toyota laboratory in Brussels.

The second project is related to a polarized eye that has a fish eye view. The main feature of the eye is that the central area has a high resolution which goes down along the radial directions. The third project is called MIRROR, which studies the sensor-motor control mechanism of human beings, and applies it to robot manipulators for visual and grasping interaction. For that project, a PUMA arm, equipped with robotic hands and eyes, has learned to grasp objects with different shapes (Fig. C.41).

The Mechatronics and Automatic Control LABoratory (MACLAB) led by Professor Giorgio Cannata

The laboratory focuses on robotic components and mechanisms that improve the performance of robots. The first robotic device is a robotic hand that is equipped with tactile sensors. The sensors are based on silicone-type soft material that can detect the touch to its surfaces. The second robotic device is a pair of robotic eyes each with four DOF (Fig. C.42). The eye design has been driven by the goal of emulating the kinematics and muscle/tender actuations of human eyes. The idea is that human eyes have six muscle/tenders to control the eyes, but four of them play primary roles. The group thus uses four tenders sliding along the eyeball to control the motion of the eyes and to verify that four tenders are sufficient for the motion of the robotic eyes.
The Laboratory of Robotics and Automation led by Professor Giuseppe Casalino

The laboratory is the largest among all the five groups and is involved in a number of topics including the following:

a) Coordination of two robot manipulators (Fig. C.43).

b) Fine manipulation planning and control for fragile object grasping using robotic hands.
c) Learning control which improves the performance of robotic hands through repeated executions to reduce errors in motion.

d) Visual servoing and active vision based on stereo-vision for robot to work in unstructured environments.

e) Teleoperation for presence of human operator in a robotic system for optimal performance.

f) Closed loop control of nonholonomic systems for navigation of car-like vehicles and underwater vehicles.

g) Team control of multiple mobile robots for increasing the effectiveness of coordinating robots in performing certain tasks.

The Laboratorium led by Professors Pietro Morasso, Renato Zaccaria, Vittorio Sanguineti, and Antonio Sgobissa

The laboratory works on mobile robotics, computational neuroscience, neural control of movement and rehabilitation, and neuroengineering. In the laboratory, we saw a manipulator interacting with human arms with different impedance settings for haptic control. The activity was supervised by Professor Morasso who coordinated with Professor Neville Hogan of MIT. The latter has been in the field of impedance control for a long time.

The research efforts of the Laboratorium have also been on outdoor navigation using vision sensors for localization and mapping. The visiting team saw a video that showed a mobile robot moving autonomously in an outdoor environment. At the time of visit, the robot was to be tested at an airport for the purpose of autonomous ground transportation there.

SUMMARY

The University of Genova has a wide scope of research activities in robotic research. The activities are primarily conducted in the Department of Communication, Computer and System Sciences. Research activities are distributed in five laboratories each led by faculty members. Notable research activities include sensor-motor control; smart robotics devices such as eyes and hands; mobile robots; coordinating robots; human-robot interaction; and sensor and computer vision.
BACKGROUND

The University of Girona was established in 1991 as a regional public university in Catalonia, Spain. The University of Girona has seven major schools: Faculty of Sciences, Faculty of Business and Economic Sciences, Faculty of Education Sciences, Faculty of Law, Faculty of Arts, Advanced Polytechnic School and University School of Nursing, as well as a number of research and educational centers and institutes that run research programs and support doctoral programs. The University includes 18 departments that organize the degree programs. The Department of Electronics, Computer Sciences and Automation includes the faculty that are most involved with robotics research.

Overview of the Visit

Our visit to the University of Girona included a meeting with Dr. Joan Batlle, the rector of the university and former director of the Computer Vision and Robotics group. Professor Batlle was very helpful and provided a perspective on the growth of this research area at the University, as well as the plans for growth of research at the university as a whole. Funded research programs in interdisciplinary areas are a strategic priority of the university. In addition, the province of Catalonia has a priority for growth of modern technologically based industries. A technology incubator is being built near the university campus, and the new underwater robotics laboratory is located at that site.

OVERVIEW OF CURRENT ROBOTICS RESEARCH

The Computer Vision and Robotics group develops real-time computer vision and image processing systems with applications such as object, pattern, color and shape recognition and tracking of mobile objects. Fields of application include underwater robotics, biomedicine and security-related systems. Systems are developed to improve the autonomy and mobility of disabled people, while others are used with autonomous and teleoperated vehicles for industrial and research applications. Garbí is an underwater robot developed in collaboration with the UPC. Garbí is used for underwater observation and to collect samples. The autonomous and teleoperated robots have transport, industrial and security-related applications.

Underwater Robotics Laboratory

In the experimental work of the laboratory, two underwater robots have been developed. The first one, Garbí, was conceived as a remotely operated vehicle (ROV) for inspection purposes. More recently effort has centered on building control architecture for autonomy, converting Garbí to an autonomous underwater
vehicle (AUV). The second prototype, URIS, was designed as an AUV. The URIS robot has very small dimensions permitting experimentation in small water tanks, and therefore, fast testing of the systems. These two platforms are used to investigate several research activities in underwater robotics. The laboratory has its own experimentation center including a swimming pool and an underwater supervision and control room. The main research topics that are currently being studied in the Underwater Robotics lab are: control architectures for autonomous and teleoperated robots; artificial intelligence techniques applied to robot control; robot dynamics and identification; real-time 3D hardware in the loop simulation; simultaneous localization and map building; and mission control.

Figure C.44. Garbi AUV.

Figure C.45. URIS underwater vehicle at the experimentation center.

One application of this research is the use of an ROV for the inspection of a hydroelectric dam. This is a joint project between the Computer Vision and Robotics Group of the University of Girona (UdG) and the Research, Development and Technological Transfer Center (CIFATT) of IPA Cluj in Romania. The experiments involved the inspection of the hydroelectric dam of Cluj and were carried out during November 2002 with the aim of evaluating the viability of the underwater robotic technology for wall dam inspection. The experiments were used to collect video data about the wall of the dam as well as to study the desired characteristics of an ROV for this kind of application.
The Garbí was first conceived as an ROV for exploration in waters up to 200 meters in depth. Control architecture is being implemented to transform this vehicle into an AUV. Garbí was designed with the aim of building an underwater vehicle using low-cost materials, such as fiberglass and epoxy resins. To solve the problem of resistance to underwater pressure, the vehicle is servo-pressurized to the external pressure by using a compressed air bottle, like those used in scuba diving. Air consumption is required only in the vertical displacements during which the decompression valves release the required amount of air to maintain the vehicle's internal pressure equal to the external. This vehicle can also be equipped with two arms, allowing the vehicle to perform object manipulation tasks through teleoperation. The vehicle incorporates four thrusters: two for performing horizontal movements (yaw motion) and two for vertical movements (Z-axis). Due to the distribution of weight, the vehicle is stable in pitch and roll. For this reason the vertical and horizontal movements are totally independent. The robot has a color camera fixed to the front. The dimensions of Garbí are 1.3 meters in length, 0.9 meters in height and 0.7 meters in width. The vehicle has a maximum speed of 3 knots and its weight is 150 kg.

The URIS is an ROV developed in this laboratory, and is used extensively as a platform for underwater vision experiments. The URIS is 35 cm in diameter and weighs 35 kilograms. The URIS is controlled through an umbilical that provides power, Ethernet communications, and video. It has three degrees of freedom of motion, and supports two video cameras, altimeter, pressure, and differential global positioning system (DGPS) sensors.

**Underwater Vision Laboratory**

Research is being conducted on the application of computer vision methods to underwater systems. Two different projects, developed under European and Spanish Govt.-supported funding, are focusing on the development of photo mosaics. A mosaic is a composite image that incorporates many individual images into a full visual map. Initially, building photo-mosaics of the ocean floor was initiated in the lab to serve as motion sensor to let the vehicle know how it is moving. This proved to be a very efficient and low-cost sensor to enable station-keeping or local navigation of the vehicle. Simultaneous localization and mapping (SLAM) and sensor fusion techniques are used to integrate measurements from the different available sensors and optimally estimate the trajectory of the robot. The national project aims to simultaneously estimate the vehicle motion and map regions with high relief and topographical variations. On the other hand, the European project aims to build large-scale photo-mosaics for characterizing and monitoring hydrothermal vent environments along the Mid-Atlantic ridge close to the Azores archipelago. The photo-mosaics obtained after the estimation of the vehicle trajectory have proved to allow the geological analysis of the ocean floor structure, obtaining a global viewpoint of the interest site. At the same time, underwater photo-mosaics provide high-quality images of georeferenced areas for the study of biological communities. The lab has developed a library to efficiently handle large-scale mosaics, with more than 40 billion pixels, using a standard computer. Sensor fusion techniques are being developed to combine navigation data, images of the ocean floor, seafloor bathymetry and acoustic imagery.

**Mobile Robotics and 3D Perception Laboratory**

The main objective of this laboratory is to study the geometrical relations that allow the perception of the three-dimensional world by means of computer vision. Research on algorithms based on projective calibration theory is one theme of this work.

**Basic Research Topics in the Computer Vision and Robotics Group**

*Simultaneous localization and map building* develops and implements spatial localization and mapping in support of the navigation of underwater robots.

*Mission Control* acts as the interface between the user and the control system. Work in this field is focused on the development of different strategies and the study of the properties of planning and reliability. Future work will include the design and the development of mission control component for robots developed in the laboratory.
Multi-AUV 3D Graphical Simulator supports development and programming of AUVs. The use of a real-time simulator can help close the gap between off-line simulation and real testing using the already implemented robot. A real-time graphical simulation with a “hardware in the loop” configuration supports the testing of the implemented control system running in the actual robot hardware. This group has designed and implemented NEPTUNE, a multi-vehicle, real-time, graphical simulator based on OpenGL that allows hardware in the loop simulations.

Artificial Intelligence techniques are applied to robot control in support of guidance behaviors for the robots. These methods were initially manually implemented using fuzzy logic, and now use machine learning techniques for the online, automatic learning of the sense-action mapping used to implement the robot behaviors. Reinforcement learning (RL)-based behaviors support the Semi-Online Neural-Q learning algorithm (SONQL). In this algorithm a neural network is used to solve the generalization problem, and a learning sample database is included in order to avoid the interference problem.

The study of the hydrodynamic equations of motion describes the underwater movement of the robot and forms the basis for control. Thrusters have been modeled using an affine model and take into account the interaction with the robot hull. For the identification of the Garbi and URIS models, several uncoupled experiments were carried out. Then, the main dynamic parameters for each degree of freedom, were identified using the uncoupled equation of motion, then were extended to the full hydrodynamic equation.
BACKGROUND

Heriot-Watt is the eighth oldest higher education institution in the U.K. It was established in its current form in 1966, but its origins date back to 1821 through the School of Arts of Edinburgh. The programs include research areas in engineering and physical sciences and in management and languages. The University was recently ranked third in Scotland by the Financial Times. Major research initiatives are concentrated in focal areas including photonics and new optics-based technologies, business logistics, technical textiles, advanced robotics, nano-science and technology, proteomics and nutrition microsystems, biomimetics, virtual reality and engineering design. The Edinburgh campus is home to Europe’s first research park, which has created 1,000 jobs and has an annual total revenue of £63 million. There are facilities for new business start-up companies at the Edinburgh and Scottish Borders campuses.

Overview of the Visit

The visit was hosted by Professor David Lane, Director of the Ocean Systems Laboratory. An overview of programs and tour of the laboratories provided a comprehensive review of both basic research and key applications under development at the laboratory.

OVERVIEW OF CURRENT ROBOTICS RESEARCH

The Ocean Systems Laboratory (OSL) is a center for research, development and exploitation of acoustic, robotic and video-imaging systems, with particular emphasis on 1, 2 and 3D signal processing, control, architecture and modelling. With a staff of 36, the laboratory works internationally with industry, government and research organizations. It aims to develop novel technology for subsea, defense and other industry applications, and to actively educate students in these areas.

Computer vision, sonar and image processing are major research themes that the laboratory has been actively developing to automate deepwater operations. In recent years, the OSL has been involved in using sonar systems to track and classify objects, to provide reactive path planning and to perform concurrent mapping and localization. In the field of vision the OSL has developed algorithms for reconstructing 3D shapes from 2D image sequences and for underwater robot position control from real-time processing of video data (visual servoing). Image processing techniques have been exploited to automatically recognize interesting seabed features and to fuse sonar and laser range data.

Key projects that were discussed at the site visit included: AMASON, Autotracker and ALIVE.

AMASON

AMASON (Advanced MApping with SONar and Video) supports research, implementation and evaluation of a modular, reconfigurable multi-sonar and video sensor system, with advanced data processing algorithms.
implemented within a geographic information system (GIS). The goal is to develop a plug-and-play system that will be readily deployable from remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs).

![Figure C.48. Mosaicing of multi-image dataset shows detailed structure on ocean floor.](image)

Major topics of research are rapid object and region characterization, classification and mapping/mosaicing in large concurrent data sets from video, sidescan, parametric sub-bottom and multibeam bathymetric sonars. Fusion of feature and symbolic data will be used to improve confidence in detected events of scientific interest. The feature detection, classification and data fusion algorithms will be implemented within a GIS environment. Raw and refined data will be georeferenced, and legacy data sets could be used to improve scientific monitoring and prediction. The goal is to implement the software suite on portable notebook computers. A modular systems architecture will ensure a scaleable and reconfigurable system.

Scientific validation on trawling impacts, sediment stability and coral carbonate mounds are examples of implementation of this system.

**Autotracker**

The need for fast communication and transport of energy has resulted in an increasing amount of subsea installations (cables and pipelines). The subsea network is especially developed in certain geographic areas including the European seas (Baltic and North Seas, Atlantic Ocean and Mediterranean Sea), Gulf of Mexico and East Chinese Sea. Several parts of these areas are located in deep water (500–3500 m).
To maintain the installations in safe and reliable condition, preventive maintenance inspections are needed. Current inspection technology deploys shipboard monitoring sensors either from a free-flying surface-towed platform (ROTV), which significantly degrades in quality, or from an ROV, which requires a survey vessel with a large crew. Shipboard inspection technology is not economically effective in water depths greater than 500 m, and with oil exploration and development activity now moving into even deeper areas, an alternative approach is required. The Autotracker system under development would link imaging and mapping, route surveys prior to installation of pipelines and cables, with inspection of the subsea installations during and after the installations.

**ALIVE**

Underwater interventions below 350 m or in harsh conditions (strong currents for example) are now conventionally performed by ROVs to carry out various tasks such as inspection, maintenance, object collection, etc. Such ROV operations are heavy and costly due to the necessity of having a sophisticated support vessel that has to remain on station above the ROV.

The project is conducted in conjunction with Cybernétix (Marseille, France) and Institut Français de Recherche pour l’Exploitation de la Mer (French National Institute for Marine Science and Technology, IFREMER) (Toulon, France), and a detailed description of the vehicle is included in the Cybernétix site report. This program will develop a light intervention vehicle, autonomous in energy and piloted from the surface through a bi-directional acoustic link, capable of reaching a fixed target on the sea bottom (e.g. wellhead, benthic station, wreck, pipeline, etc.) and supporting a tele-manipulation unit. Typical tasks will be routine inspection and light maintenance, as well as object collection. This vehicle would have no physical link with the surface and could be supported by a light and fast support ship. The OSL contributes to this collaborative program through development of underwater inspection and intervention.
Figure C.50. The SeeTrack system provides a comprehensive applications environment for acquisition and analysis of undersea data.

Commercialization

A commercial company, SEEByte Ltd (http://www.seebyte.com), is a major participant in many of the projects initiated at the OSL at Heriot-Watt.

Key products that have evolved from OSL research and which are provided through SeeByte include:

1. SeeTrack is a post-processing tool for rapid on-site data reduction, analysis and data fusion of sensor data, including sidescan, forward look sonar, imaging sonar and video. It is a modular system and is designed to perform on both notebook and desktop environments. It has been employed during 2000 and 2001 in the U.S. Field Battle Experiments, NATO SACLANTCEN GOATS 2000 trials, Kernel Blitz 2001 and AUV Fest 2001.

2. SeeNav is a navigation tool that can operate in real-time and post-processing modes. It is modular and uses various navigation sensors and the environment to compute the position. It has already been successfully used to produce high-quality and highly accurate geo-referenced sidescan sonar mosaics.

3. RECOVERY is a set of software tools for fault detection and diagnosis in numerous industrial applications, driven by the need to reduce costs, comply with safety and environmental legislation, and maintain company image/profile. Manual diagnosis may be beyond the capabilities of first-level technicians (craftsmen), there may be insufficient time, or the system may be remotely situated.
Site: IFREMER
Institut Français de Recherché pour l’Exploitation de la MER
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Date Visited: April 27, 2005


Hosts: Dr. Vincent Rigaud, Director of the Underwater Systems Department, Direction of Operations, Email: vincent.rigaud@ifremer.fr

BACKGROUND

Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER) is a public institute of the French government established in 1984 under the joint supervision of four ministries: Research, Agriculture and Fisheries, Amenities and Transport, and Ecology and Sustainable Development. Its missions are to conduct and promote basic and applied research, make expert assessment reports, and undertake programs for technological and industrial development. These missions include the development and testing of marine technology.

The IFREMER laboratory in Toulon was established in order to provide a center of research and marine systems support on the Mediterranean. The current facility was constructed at à La Seyne sur Mer, within the industrial port zone of Bregaillon. This site provides geographic access to the Mediterranean and also provides the capability for rapid deployment and efficient testing of new systems and technologies.

Overview of the Visit

The visit to IFREMER included an overview of technologies and research programs followed by an extensive tour of facilities and vehicles in the laboratories.

OVERVIEW OF CURRENT ROBOTICS RESEARCH

Major projects on vehicle development and experimentation include:

Victor 6000

The Victor 6000 is a deepwater remotely operated vehicle (ROV) instrumented for modular support of scientific research including high-quality optical imaging. The working depth is up to 6,000 meters and the maximum speed is 1.5 knots. There are three major camera systems on board as well as sensors for attitude, depth, and sonar. Two manipulators are onboard, one with seven degrees of freedom (DOF) and one with five DOF.

ALIVE

ALIVE (Autonomous Light Intervention VEhicle) is designed (in conjunction with Cybernétix) for performing light interventions on deepwater subsea facilities without the requirement for a dedicated support vehicle. This project is conducted jointly with Cybernétix (Marseille, France) and Herriot-Watt University (Edinburgh, U.K.). A detailed description of the ALIVE vehicle is included in the Cybernétix site report.
C. Site Reports—Europe

Figure C.51. Victor 6000 (left) is a deepwater ROV developed at IFREMER. ALIVE (right) has been developed for manipulation tasks on deepwater subsea facilities.

NAUTILE

NAUTILE is a subsurface habitat for scientific research at depths of up to 6,000 meters. It supports two pilots and one passenger. The planned scientific missions include surveillance, physical measurement and fine bathymetry, support for a large number of different scientific instruments, support for off-shore work, tracking of pipes and cables, and support and assistance for deepwater ROVs and autonomous underwater vehicles (AUVs).

Figure C.52. NAUTILE is a habitat for scientific research at depths of up to 6,000 meters.

ASTER

ASTER is a newly developed AUV that will be used for coastal surveys at depths of up to 3,000 meters. The length is 4.5 meters and weight is 703 kg. The predicted speed is up to 5 knots per hour. The ASTER will be capable of carrying instrumentation appropriate to site surveying, including side scan sonar, multibeam echo sounder, sub-bottom profiler, Conductivity, Temperature and Depth (CTD), Acoustic Doppler Current Profiler (ADCP), fishery sounder, and water sampling devices. The navigation is provided by long range acoustic telemetry, inertial Doppler dead reckoning, and inverse ultra-short baseline (USBL) navigation. Safety considerations include autonomous relocation pinger, acoustic communications modem, radio frequency (RF) beacon, and telescoping mast.
Figure C.53. Photographs of the ASTER AUV in the laboratory. A view of central body hosting instruments and computational capability, (left) view of tail section shows thruster and control surfaces (right).
Site: INRIA
Institut National de Recherche en Informatique et en Automatique
2004, Route des Lucioles-B.P. 93-06902
Sophia Antipolis Cedex, France

Date Visited: April 28, 2005


Host: Dr. Claude Samson, Director of Research Project ICARE, Tel: +33 4 92 38 77 36,
Fax: +33 4 92 38 76 43, Email: Claude.Samson@inria.fr

BACKGROUND

The laboratory visited is a part of Institut National de Recherche en Informatique et en Automatique (INRIA), which is a major French national research institute on information and automation. INRIA has a number of regional institutes. The one we visited is located in Sophia-Antipolis, located in southeastern France. Our host Dr. Claude Samson leads the research project Instrumentation, Control and Architecture of Advanced Robots (ICARE). The project is only one of a few which are related in robotics research and conducted at INRIA. Unfortunately, we only had time to visit Dr. Samson’s laboratory. The ICARE project, according to its web site, is “dedicated to the study of the problems of command and control in autonomous mechanical systems, with a special but not exclusive focus on robotics. The main target is to develop a methodology for the design and integration of each link in the chain.”

RESEARCH ACTIVITIES OF THE ICARE LABORATORY

The ICARE laboratory has four researchers, six PhD students and one assisting engineer. Research activities of the ICARE project focus on: robot and control, control of nonlinear systems, and perception and autonomy. The more detailed areas which the laboratory currently covers include the following:

1977 Robot control
1978 Sensor-based autonomous robots
1979 Robotic devices for enhancing robot performance
1980 Nonlinear control and stabilization for lower-level control of robots
1981 Perception for sensor-based modeling and control
1982 Robot localization, environment modeling and navigation (SLAM)
1983 Simulation and experiments for various control and navigation schemes

The laboratory has two mobile robots for research. One is an indoor mobile robot called ANIS (Fig. C.54) and the other is an outdoor mobile robot called CyCab which is essentially an electric car.

Figure C.54. The ANIS indoor mobile robot.
The most notable feature of the ICARE project is in its navigation scheme of nonholonomic mobile robots in tracking a target vehicle. The scheme is fundamentally different from popular approaches that many laboratories in the world use. These approaches first manage to understand the geometric features of the target using various sensing technologies. Then a path is planned for the mobile robot to follow the target by continuously matching the image acquired by visual sensors with the stored geometric model of the target. In such approaches, conventional control strategies are considered not suitable for the navigation purpose.

The INRIA approach takes a different perspective that does not specify the path of the mobile robot, but instead uses a feedback control scheme. The control scheme always attempts to stabilize inside a neighborhood of zero the difference between the current position and orientation of the mobile robot and the situation of a target frame associated with the target vehicle. The size of this neighborhood is adjustable at will—it is one of the control parameters—and the path is produced in the process of control automatically. A noticeable difference with other feedback control methods is that exact zeroing of the tracking error is not the primary objective. A reason for considering a slightly less ambitious objective is to comply with the inherent impossibility for a nonholonomic vehicle—such as a unicycle-like, or a car-like, mobile robot—to move laterally instantaneously, whereas the (omni-directional) target frame is free to do so. Such an objective is thus coherent with the fact that perfect trajectory tracking by the mobile robot cannot be accomplished in general, and is also coherent with the possibility to automate manoeuvres in a feedback fashion in order to achieve tracking with arbitrary good (but not perfect) precision whatever the motion of the target vehicle. The ICARE project uses a control strategy that is based on the transverse function control approach. The approach establishes a general framework for the design of a control law which yields practical stabilization for nonlinear controllable systems. Estimation of the target’s velocity based on visual data is also used for the purpose of target tracking and improvement of the performance of the control scheme. This unique control scheme has been implemented on the unicycle-like mobile robot ANIS and subsequently showed smooth motion in tracking the desired target in laboratory demonstration.

In addition to the ANIS mobile robot, the host also showed a video that demonstrated the CyCab in tracking another man-driven vehicle by using computer vision to match a desired geometric model posted on the back of the leading cab.


SUMMARY

ICARE studies various topics of robotics research including robot and control, control of nonlinear systems, and perception and autonomy. The project has a unique scheme in the navigation of mobile robots for tracking a moving target. The scheme designs a control law using the transverse function control approach plus estimation of the target’s velocity using sensing data in real-time. It can stabilize the mobile robot in tracking a non-feasible trajectory of the target and has been proven effective in laboratory demonstration.
Site: University of Karlsruhe  
Universitaet Karlsruhe (TH)  
Institute of Computer Science and Engineering (CSE)  
Forschungszentrum Informatik Karlsruhe (FZI)  
Research Center for Information Technologies  
http://www.iaim.ira.uka.de  
http://www.fzi.de

Date Visited: April 28, 2005

WTEC Attendees: V. Kumar (Report author), G. Bekey

Hosts: Professor Dr.-Ing. Rüdiger Dillmann, Chair of Industrial Applications of Informatics and Microsystems (IAIM) at CSE, FZI Director,  
Email: dillmann@ira.uka.de; dillmann@fzi.de

BACKGROUND

The Research Environment

Professor Dillmann is chair of a large research group within the academic department of computer science (Informatics) at the Universitaet Karlsruhe and the Technology Transfer Center (FZI: Forschungszentrum Informatik). Thus the research stuff is divided into two groups, one at the University (Institute of Computer Science and Engineering (CSE) / Industrial Applications of Informatics and Microsystems (IAIM): chair Prof. Dillmann) and one at FZI. The FZI offers the opportunity to establish spin-off companies (currently there are four companies established in such a way). Each head of an FZI department is also a professor at the University of Karlsruhe.

Dr. Dillmann has established a large network of cooperative research programs with researchers elsewhere in Europe. These include Raja Chatila in France, Henrik Christensen in Sweden, Paolo Dario in Italy, Henrik von Brussel in Belgium, Giulio Sandini in Italy, Roland Siegwart in Switzerland and others. He also collaborates closely with the Fraunhofer Institute for Information and Data Processing in Karlsruhe (http://www.iitb.de) and the Forschungszentrum Karlsruhe (http://www.fzk.de). His other contacts include Advanced Telecommunications Research Institute (ATR) in Kyoto/Japan (Mitsuo Kawato and Gordon Cheng), Chris Atkeson and Jessica Hodgins at Carnegie-Mellon University (CMU), Stefan Schaal at the University of Southern California (USC) and George Lee at Purdue. His work is supported by grants from the European Community, the German government as well as the State of Baden-Wuerttemberg and industry.

MAJOR RESEARCH PROJECTS

Humanoids

Prof. Dillmann has a long-standing interest in various aspects of humanoid robotics. We saw ARMAR, a two-arm robot on a wheeled base in a kitchen environment. The robot has 23 mechanical degrees of freedom (DOF). The robot consists of five subsystems: head, left arm, right arm, torso and a mobile platform. The upper body of ARMAR has been designed to be modular and lightweight, while approximately retaining the size and proportion of an average person. The head has two DOF arranged as pan and tilt and is equipped with a stereo camera system and a stereo microphone system. Each of the arms has seven DOF and is equipped with six DOF force torque sensors on the wrist. The current mobile base of ARMAR consists of a differential wheel pair and two passive supporting wheels. It is equipped with front and rear laser scanner (Laser Measurement System (LMS)). Furthermore, it hosts the power supply and the main part of the computer network.
The robot is being trained to go to the refrigerator and retrieve objects, load dishes into the dishwasher, and place items in the microwave. None of these goals has yet been achieved, but the robot’s speech interface is working, and it navigates well on its mobile base. The robot is used as a testbed for the integration of motor, perception and learning components necessary for multimodal human-humanoid interaction in the German humanoid project SFB588. At the moment algorithms for dual-arm motion coordination, recognition, localization and tracking of colored and textured objects are being investigated, implemented and tested. The robot is equipped with five-fingered hands capable of eight DOF motion using hydraulic actuators.

Figure C.55. The humanoid robot ARMAR.

*Other Platforms*

Dillmann’s group has developed several autonomous wheeled platforms capable of navigating hallways with obstacles, some capable of automatically going to charging stations and plugging themselves in.

The lab has developed, in joint cooperation with the company SwissLog Telelift, a low-profile flat-top vehicle capable of sliding under a large container, raising it using an elevator platform and then transporting it. Dillmann’s lab has been responsible for the on-board control system including laser scanner based navigation and logistics of a multiple automatic guided vehicles (AGV) installed in hospitals worldwide (e.g. Houston, Los Angeles, Leipzig, Varese, Trondheim, Dessau and Geifswald).
Pipe Inspection Robots

Prof. Dillmann’s lab has developed several articulated, snake-type robots for pipeline inspection. Some are now commercially available and used to inspect water pipes and oil pipelines (including the Alaska pipeline).

Current work is concentrated on enabling the system to work in an unstructured environment. A multi-articulated system with six links will be used for inspection tasks in sewer pipelines.

Legged Locomotion

There are labs dedicated to the development of control systems for four- and six-legged robots, as well as bipeds. The emphasis appears to be in the application of artificial muscles (McKibben-type muscles with a rubber shield), reduction of size and weight, and joint design. Historically, they have fabricated several of the Lauron-type six-legged machines usually associated with Friedrich Pfeiffer at the Technical University of Munich (TUM). Apparently there has been a long-term cooperative effort between the two labs.
Up to now 10 six-legged walking machines have been built and distributed: three to museums and seven to universities or research groups in Germany and Europe.

**Medical and Surgical Robotics**

Several projects involve cooperation with medical personnel on visual identification of target areas for surgery on the skull, estimation of spine and neck muscle properties to determine the extent of whiplash injuries, and automatic calibration of medical instruments with imagery for image-guided surgery.

**COLLABORATIVE PROJECTS**

Professor Dillmann has an extensive network of collaborators on many projects. The big projects are:

- Collaborative Research Center on Learning and Cooperating Multimodal Humanoid Robots “SFB588,” which was established by the DFG in 2001 and will be run for 12 years (coordinator: Rüdiger Dillmann)
- Cogniron Project (funded by the EU, led by Dr. Raja Chatilla at the Laboratoire d’Analyse et d’Architecture des Systèmes (LAAS), Toulouse)
- PACO-PLUS (funded by the EU, coordinator: Rüdiger Dillmann)

Other collaborative research projects in Germany include:

- Robots in Surgery (SFB 414 in Karlsruhe)
- Telepresence and Teleaction Systems (SFB 453 in Munich)
- Autonomous Dynamic Walking (Munich)
- Situated Artificial Communicators (SFB 360 in Bielefeld)
- Robotic Systems for Handling and Assembly—High Dynamic Parallel Structures with Adaptronic Components (SFB 562 in Braunschweig)
- Spatial Cognition: Reasoning, Action, Interaction (Transregio SFB 6023 in Bremen/Freiburg)
- Cognitive Cars (SFB in Karlsruhe/Munich)
Professor Dillmann also collaborates with other faculty at the University of Karlsruhe and the Fraunhofer Institute.

**Prof. Dr.-Ing. H. Wörn, Universitaet Karlsruhe, Institute of Process Control and Robotics**

Prof. Wörn worked for many years at Kuka. He now directs a number of robotics projects, including development of robot hands and artificial skin for robots. The skin is a soft material overlaid on a copper skin (piezo-resistive force sensor) that deforms under pressure and locally changes its electrical resistance. Several hundred such sensors are multiplexed for pressure sensing.

Prof. Wörn also collaborates with Prof. Dillmann on studies of robot-aided head surgery. Professor Wörn has also worked on the development of a 3–4 cm sized robot for micromanipulation. He is presently the coordinator of the I-SWARM project, a multi-institution project funded by EU, in which he is working toward the simulation and eventual development of swarms of as many as 1,000 robots (See http://www.iswarms.org).

**Dr. Helge Kuntze, Fraunhofer Institute, IITB, Karlsruhe**

The major robotic projects at the Fraunhofer IITB are:

- Humanoids (supported by the DFG collaborative project SFB588)
- Neuro-fuzzy-based supervisory robot control architecture
- Pipe inspection—they also work on multisensor pipe inspection systems, while Dillmann concentrates on the mechatronic aspects
- Multisensor homeland security inspection robots for periphery of factories
- Telepresence, nonlinear estimation, localization and tracking, distributed phenomena, recognition of robot intention
- Telepresence—includes motion compression; path transformation; allows human to walk a transformed path while guiding robot motion

**OVERALL EVALUATION**

There is a very large concentration of robotics researchers in the Karlsruhe region, including Dillmann’s lab, the Fraunhofer Institute, a major nuclear research center and various industries. Dillmann clearly believes the robotics is on a growth trajectory in Germany, where the strongest groups include Karlsruhe, Stuttgart (for industrial robotics), Munich and the German Aerospace Center (DLR). Other centers include Aachen, Darmstadt, and Berlin. He also believes that true robot household helpers and medical assistants are only two or three years away.

In our opinion Prof. Dillmann is a very successful entrepreneur, who has succeeded in building a major applied robotics research center. His research activities span a wide range of disciplines such as integrated mechatronics design, autonomous robot systems, service robots, walking machines, humanoids, machine learning, human-robot interaction, robot programming by demonstration, and simulation for medicine applications. The three projects mentioned above (SFB 588, Cogniron and PACO-PLUS) focus on fundamental issues related to the design of highly integrated robotics platforms capable of developing and learning perceptual, behavioral and cognitive skills and communicating with humans and other artificial agents in a human-like way.

Dillmann believes Japan is strongest in humanoids and service robots, while U.S. leads in space and military robotics and Germany is strong in industrial and service robots. Industrial robot companies in Europe (primarily Kuka and ABB) collaborate with universities, while FANUC in Japan does not. This puts German researchers at an advantage.
OVERVIEW

The Center of Autonomous Systems (CAS) at KTH, Stockholm, was established in 1996 with Professor Henrik Christensen as the director. It brings together four departments: Computer Science, Electrical Engineering, Mathematics, and Mechanical Engineering. It is governed by a board consisting of members from academia and industry, and has an advisory board consisting of distinguished academics from all over the world. CAS aspires to be one of the top five centers in basic research, generating around five to eight PhDs per year. About two-thirds of its funding is shared equally by EU and the Swedish Foundation for Strategic Research (SSF), while the remaining third comes mostly from defense. Only 3% of the funding comes from industry. The group includes six full professors, one associate professor and one assistant professor, with two to four post-doctoral researchers and between 16 to 18 doctoral students.

Research Thrusts

CAS strives to strike a balance between basic research on component technologies and integration of methods into systems. It has three research thrusts: field robotics, service robotics, and technology transfer.

Field Robotics

The interest in field robotics is driven by the strong vehicle industry and related field applications in Sweden. The basic challenges in field robotics are: (a) Robust perception; (b) Long-term autonomy; and (c) Large-scale mapping for large spaces. The CAS has an ongoing project that involves the integration of global positioning system (GPS) information, range from laser range finders, heading from compasses, and odometry measurements, with the goal of mapping large (200 m x 300 m) spaces. They are able to map such spaces with accuracies better than 10 cm.

CAS has two packbots and is working closely with iRobot. They are testing and conducting usability studies on wearable interfaces with soldiers.

Service Robotics

The basic challenges include (a) mapping and navigation; (b) mobile manipulation; (c) user interfaces; (d) autonomy; and (e) architectures for integration.

The work on mapping and navigation, in particular, is innovative. It is formulated as a minimization problem on a graph and is potentially scalable, unlike other competing methods, to large spaces. It should also be noted that the CAS produced the International Conference on Robotics and Automation (ICRA) 2003 best paper award on dynamic modeling and simulation of multifingered grasps.

Technology Transfer

The CAS has many ongoing interactions with industry. The technology transfer examples include the Electrolux Navigation System and the PerMobil Wheelchair Control. They also work closely with ABB, the second largest manufacturer of industrial robots.
EU Activities

The CAS director, Dr. Christensen, is the coordinator of the EU Network of Excellence (EURON), which involves 140 institutions and enables the integration of research and education across institutions and establishes connections to industry. He is also the author for the Robotics Research Roadmap for the EU. Dr. Christensen is also a participant in many EU research projects including:

a. Cogniron: Cognitive robotics for autonomy;
b. Neurobotics: Integration of neuroscience and robotics for assistive devices;
c. CoSy: Cognitive Systems for cognitive assistants
Site: LAAS-CNRS
Laboratoire d'Analyse et d'Architecture des Systèmes
Centre National de la Recherche Scientifique
7, avenue du Colonel Roche
31077 Toulouse Cedex 4, France

Date Visited: April 26, 2005

WTEC Attendees: B. Wilcox (Report author), R. Ambrose, Y. T. Chien, D. Lavery, M. Dastoor

Hosts: Raja Chatila, Head, Robotics and Artificial Intelligence Group,
Tel: +33 (0)5 61 33 63 44, Fax: +33 (0)5 61 33 64 55, Email: raja@laas.fr
Malik Ghallab, Director, Programme National Robotique et Entités Artificielles,
Tel: +(33) 561.336.271, Fax: +(33) 561.336.455, Email: Malik.Ghallab@laas.fr
Simon Lacroix, Field Robotics, Planetary Exploration, and Aerial Robotics,
Frederic Lerasle, Cognitive Robotics and Human-Robot Interaction (with Raja Chatila),
Felix Ingrand, Temporal Planning and Control (and demo of Planetary Rover DALA
and Mission Planning and Control),
Nic Simeon, Motion Planning and Molecular Motion,
Jean-Paul Laumond, Motion Planning for PLM and Digital Actors,
Sara Fleury, Interactive Robot Rackham and Cognitive Robotics,
Florent Lamiraux, HILARE 2 Robot and Trailer Motion Planning

BACKGROUND

The meeting started with welcome and introductory remarks by Malik Ghallab, the director of the
Programme Robotique et Entités Artificielles (ROBEA). Laboratoire d'Analyse et d'Architecture des
Systèmes (LAAS) was founded in 1967. Toulouse has the second oldest university of France, after Paris.
Centre National de la Recherche Scientifique (CNRS) is the largest scientific organization in Europe, with
1,260 laboratories, 67,000 workers, of which 26,000 are at CNRS. Of those, 11,600 are researchers and
14,000 are engineers, technicians and administrative staff. In all of CNRS, 23,000 are faculty (shared with
universities). The rest of the 67,000 (i.e., 18,000) are PhD students, post-docs and visiting scientists. The
overall budget is about €2.2 billion per year. LAAS is the largest CNRS laboratory, with about €26 million in
funding per year. This lab has 540 researchers and staff associated with three universities, including 200 PhD
students. There is no teaching at this site—only some graduate courses and training for research students.
They are organized into 14 groups in four main areas: Micro and Nano systems (MINAS), Control Theory,
Critical Informatics Systems, and Robots and Autonomous systems (the focus of today's meetings). MINAS
is the thrust area in micro/nano, with research emphasis on photonics, optics, microwave communications,
power electronics, chemistry, physics, and life sciences. An example of the work in that area is the detection
of physical properties from a μm drop of liquid on a cantelever beam. In the Control Theory area, they have
an exceptionally strong mathematical group, specializing in control of rockets and turbine engines, working
especially with Airbus. The Critical Informatics Systems area emphasis is on quality of service for networks.
Raja Chatila is a senior research scientist and head of the Robotics and Artificial Intelligence Group and head
of the Robotics and Systems Autonomous area (ROSA).

Raja Chatila briefly described the Robotics and Artificial Intelligence Group. It consists of 21 staff (including
12 researchers, who occasionally teach, and eight professors, with joint appointments with local universities).
They have about 30 graduate students at the present time. Also, there are four associate researchers, postdocs,
or visiting scientists. Kurt Konolige from SRI International was recently here for three quarters; Ron Arkin
from Georgia Tech is coming for 11 months. CNRS labs are always closely tied to universities, hosting
neighboring professors. The researchers and professors are civil servants, with salaries covered by the
government. The group receives about €600,000 per year from contracts for equipment, scholarships for
students, and travel.
An overall long-term objective of the Robotics and Artificial Intelligence group is the creation of an artificial being or entity. This entity should work in a real environment, uncontrolled by an external human. In a complementary view, they also see robotics as a multi-thematic field—a convergence in perception, decision-making foundations, and applications—but not necessarily integration, not necessarily real-time, sometimes covering topics that seem far away from robotics.

Simon Lacroix gave a presentation about field robotics, planetary exploration, and aerial robotics. He stated that environmental perception and modeling are very important for navigation and motion control in natural and artificial environments, whether it is for human motion, robot motion, motion for digital actors, or molecular motion. Planetary exploration research began there with “Adam” in 1993, “Lama” (on a Russian Marsokhod platform) in 1996, “Karma” (a blimp) in 2000, and recently “Dala” (a four-wheel vehicle based on the iRobot ATRV), and the COMETS project with a collection of high lift-to-drag-ratio unmanned aerial vehicles (UAVs) (Figures C.59 and C.60).

The overall focus of the work is on integration of perception to action. In the past they have demonstrated an autonomous long-range planetary rover that is able to move several hundred meters without human intervention. That system took about 10 years to develop. They are interested in systems that will behave differently in different environments, e.g. with different navigation modes that are selected according to the environment. In a smooth environment it will use simple models and plans. In a very rough environment it will use complex and accurate models, and sophisticated motion planning. Goals are expressed in Cartesian coordinates. They evaluate different trajectories, in a fashion somewhat similar to the Morphin system developed at Carnegie-Mellon University (CMU). They use visual odometry, perform terrain classification in 2D, and vision-based path tracking. Their inertial and dead-reckoning sensors are a fiber optic gyro plus odometry. With visual motion estimation—2D tracking, stereo correlation, and 3D motion estimation—they have demonstrated 1% accuracy (of distance traveled) over 100 m.
The group started working on 3D Simultaneous Localization and Mapping (SLAM) in 1996 (their earlier work on SLAM dates back to 1985). With this approach, the navigation and mapping over a 60 m loop has been corrected to ~1 cm. They match features directly in the images, not in a Kalman Filter. They are conducting substantial work with panospheric cameras. Image indexing and calibration of panoramic stereovision is a principal focus of this activity.

In the area of motion planning they have “potential” methods that work in easy terrain, but incorporation of rover orientation/motion constraints is very ad-hoc. In the area of motion execution control they showed an example of the Russian Marsokhod chassis that they used for many years going over a very large rock pile, maintaining heading in the process. They don't like the skid steering of the Marsokhod, as it is difficult to control. Current research focuses on remaining issues such as locomotion control, localization, navigation strategies, and dealing with more complex mission scenarios.

In the area of flying robots, they are experimenting with bearing-only SLAM that recovers the vehicle position history and some map information only from the bearings to landmarks, without range data. However, they feel that this approach is not relevant to ground robots, which they believe will certainly have stereo vision and thus range data.

At a high level, they are working on the interconnections between and the transition from robotics (e.g. the functional level) to artificial intelligence (e.g. the decisional level).

Phase B is about to start for the ExoMars Project. The relevant European science board has established the need for the mission. They believe it will be necessary to have a rover, of which they have proposed a substantial role in the development. The discussion digressed briefly to the Véhicule Automatique Planétaire (VAP) project that was active from 1989 to 1993, which they described as the “golden age” of robotics sponsorship by CNES (the French Space Agency).

Karma is an autonomous blimp. The good things about a blimp are that it is big, slow, safe, and requires little energy. The bad things are that it is big, slow, sensitive to winds, and needs a hangar. For Karma they created a big stereo optical bench with a camera separation of 3.2 meters that was constructed from carbon fiber composite, but they found that it stayed calibrated for only one day at a time. The stereo vision algorithm they developed specifically for the blimp was fast, but had artifacts.

They presented a taxonomy of autonomy levels (in the context of multi-robot or multi-UAV systems):

- Level 1: No autonomy, robot processes single tasks
- Level 2: Robot processes a sequence of tasks
C. Site Reports—Europe

- Level 3: Level 2 plus the ability to synchronize with other robots
- Level 4: Robot is able to process at the mission level,
- Level 5: Level 4 plus task allocation ability, with all distributed control

As part of the joint COMETS project with Spain, Germany, and Sweden, they are doing a demo in Portugal where an autonomous blimp and helicopter conduct a mission along with a teleoperated helicopter. In this first demo the autonomous system assumes the teleoperator will perform the task, but monitors execution carefully, knowing the task statement.

Raja Chatila and Frederic Lerasle next presented work in the area of cognitive robotics.

Evolution of work in personal robotics has led to the “Cogniron Project”—a European project lead by LAAS to develop a “Cognitive Robot Companion.” This robot is conceived to interact with people and understand speech and gestures. An example is the serving of drinks.

Cogniron must behave socially: it must behave in a friendly manner and make people feel comfortable (U. Hertfordshire leads); it must learn: learning skills and tasks, imitation learning (EPFL Lausanne leads); it must understand space: learning space, learning objects (U. Amsterdam and LAAS lead); it must understand what humans are doing (U. Karlsruhe leads): face, expression, gesture and voice recognition; it must communicate: conduct dialog (U. Bielefeld leads), take decisions and express intentions (LAAS leads); it must integrate all activities. There are three key experiments. In the first, a curious robot must discover new objects and try to learn about them. In the second, a home tour robot must learn its environment from a human showing a home. In the third, learning skills and tasks must be integrated (e.g. observing humans and interacting to learn a task like setting a table). The web site for this project is http://www.cogniron.org. In this discussion they did not address the work of the other centers involved in the project.

They are developing a robot that guides visitors in space museum (Figure C.61). The mobile robot uses laser in corridors plus vision-based localization using memorized quadrangles (e.g. posters) with interest points. In another setting, it performs 3D SLAM by matching points detected using the Harris corner detector.

An interesting topic is determining and ensuring acceptable social interaction distances for robots with humans. There is a series of workshops on robot safety in human environments. They believe the burden is on the robot to make it convenient for humans. Any path planning algorithm must take into account that humans might emerge from a doorway, for example, by staying on the opposite side of the corridor.

In object modeling work, they use a distributed system, a neural network where each layer recognizes more and more complex objects and structures. There is specialization in that each neuron does not learn multiple objects. It is not view-based, but rather object-based.

They use three-layer architecture: one for functional and execution, one for validation and execution control, and one for the decision level (planning and supervision).

To accomplish the learning of skills, they use “value function learning.” They embed within any visual representations the skill representation as well. When you present an apple to the system while learning a value function, it is modeled by a hierarchical representation (e.g. round, red, with a stalk), the operator concurs to provide a reward to increase the value function. Each component of recognition has no effect on the value function by itself, e.g. a soccer ball is round but not red nor has a stalk, or a red flower is not round but has a stalk. The idea is to associate actions with objects—e.g. a presented apple is for eating.

Frederic Lerasle presented a gesture and face-tracking system. It distinguishes intermittent cues from persistent but ambiguous cues. Shape and color distribution are persistent cues: skin pixel, motion, frontal face detection are intermittent cues. It combines persistent and intermittent cues to maximize robustness with particle filtering. A demonstration tracks faces in and out of full sun to deep shadow, while turning around, etc.
Gestures can be communicative or manipulative. When they are manipulative, the system must use 3D approaches to understand them. When they are communicative, both 2D and 3D approaches plus speech can be used. Their 3D models are based on a chain of truncated quadrics (non-deformable and given, not learned, but they have good properties in projections), with inner degrees of freedom to model articulations. Their 2D tracker knows, for example, the joint limits of a human arm and can create a 3D representation of an arm with single camera view. Among other things, they perform posture tracking of human figures.

Felix Ingrand, who was at SRI, and worked with NASA Ames Research Center, described temporal planning and control. He began with the question, “Why do we need an architecture?” The answer is that robots are complex, and work in real-time with exponential complexity. In the functional level each module deals with one sensor or one functionality (e.g. to manage a camera, another to do stereo, etc.), where algorithms can be broken into pieces. The execution control level sends requests to the functional units. A formal model is needed to prevent runaways, etc. Never do certain things (e.g. correlate stereo without taking images), always do others (e.g. check speeds to make sure they are within bounds). At the decisional level is a temporal task planner (called IxTeT) and a supervisor (IxTeT-eXeC). It has a representation of time and resources, a time-oriented functional representation, and a search mechanism (search in the planning space of partial-order causal links). Flexible plans are more robust to execution errors—based on constraint satisfaction programming (CSP) managers (similar to Europa and Mapgen done at NASA Ames Research Center). They can replan and recover from failures without a total replan, sometimes without even stopping. Parts of the system are distributed as open software. Their web site is http://softs.laas.fr/.

Thierry (Nic) Simeon described motion planning and molecular motion. The original combinatorial explosion recognized for motion planning for robots led eventually to the study of molecular motion. In 1980 Lozano-Perez at MIT formulated the configuration space (C-space) representation. C-space normally is higher dimensional than real space but it is easier to find connected routes from a start point to an end point. In the 1980s there were deterministic methods that featured exponential complexity, and were limited to a few DOF. In the 1990s probabilistic methods emerged that trade a limited amount of completeness for computing efficiency: Probabilistic Roadmaps (PRM, Stanford-Utrecht), visibility roadmaps, Random Trees (RRT, Illinois U.). They showed an example of manipulation task planning—sliding a bar out in many small movements from under fixed obstructions, where the bar cannot be slid out in one motion because of the obstruction of the grasp point.

In molecular motion—proteins are large deformable structures—the folding pattern and flexure patterns must be computed for the function of the molecule to be understood. This problem is of immense practical interest, since a DNA sequence defines the order of amino acids in a protein, but without computing the final 3D shape, the chemical function of an enzyme cannot be understood.

Florent Lamiraux described robot motion planning and control for non-holonomic systems (those with linear velocity constraints—e.g. wheeled vehicles with trailers, etc.).

C-space, decidability, deterministic approaches are described in the book “Robot Motion Planning” by Jean-Claude Latombe (1991). What is required is a locally controllable method where steering methods connect two points in C-space such that points that are close in C-space have a path that stays close to those points. The example they are working with is a robot with a trailer with a hinge point over the front axle. This system is “differentially flat”—by differentiating the motion of the center of the trailer you can reconstruct the configuration of the vehicle—an important concept from control theory.

LAAS was first to propose piecewise-smooth trajectories for these robots. An important issue is planning with uncertainty (due to map errors, robot localization errors, etc.). They use a potential field that pushes away from obstacles, but needs to maintain a solution that satisfies kinematics constraints.

An important practical application of this is the problem of moving Airbus A380 wings over the small country roads from Bordeaux port to Toulouse (where final assembly of the aircraft is performed). Specific examples of solutions from some of the small towns were shown.
Jean-Paul Laumond presented work in “Motion Planning for Product Lifecycle Management,” and virtual, natural, and artificial human motion.

In the 1990s they developed the “Move3D” software for generic motion planning, and spun off a startup company called “Kineo”. The product is middleware, with a focus on product development to generate long-term company revenues but also a high-value service for short-term revenues. Kineo path planning software for computer-aided manufacturing (CAM) has the automotive industry as the target market. There are only a few providers of CAM software for this large market: Dassault Systèmes, Unigraphics-Tecnomatix, PTC.

The Kineo software addresses assembly path planning problems. It recently solved in two minutes what an expert human took two days to solve; in another case a human could not find a solution, but the computer found a solution in one minute. (Typical cases include planning the motions to install the seats in a car when they don't appear to fit through the door.) It works with path planning clearances as low as 0.1 mm. Kineo is available as a plug-in to Solidworks and other computer-aided design (CAD) systems (this received the IEEE International Federation of Robotics (IFR) Award for Innovation, Barcelona, April 2005).

An example is a real-time video game of an octopus catching a mosquito. AI methods currently used by the video game industry work only in “2 1/2 D,” e.g. with only the surface seen at each point modeled. But the octopus/mosquito system is 4 x 7 DOF (this particular “octopus” only has four arms, each with seven DOF). So with AI methods the computing time grows exponentially with 28 DOF, while Kineo is based on a Monte Carlo approach and grows very slowly with the complexity of the problem.

A similar problem is to compose virtual motions for digital actors and mannequins that appear to be natural motions for humans. Human eyes are very sensitive to quality of motions. The observer must understand the emotion and action motions. Motion planning for humanoids must unify obstacle avoidance, kinematics, dynamics, and motion planning.

In lab tours the WTEC team was shown a demonstration of the museum tour guide robot, the nonholonomic tractor trailer path planning robot, and an ATRV chassis performing mission planning and control, SLAM and hazard avoidance.
Site: Oxford University  
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Date: April 26, 2005

WTEC Attendees: Y. Zheng (Report author), A. Sanderson, J. Yuh, H. Ali

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Professor Sir Michael Brady, Dept. of Engineering Science

BACKGROUND

The Department of Engineering Science at Oxford University is well known for robotics research in the community. For a long time, research activities were led by Professor Michael Brady who transferred to Oxford University from MIT in 1985. In recent years, robotics research was no longer that active as Dr. Brady shifted his research interests to medical images. In January 2003, Dr. Paul Newman joined the department, and Oxford University became active again. Before joining Oxford, Dr. Newman worked at MIT as a postdoc for two years and received a PhD in Australia under Durrant Whyte at the University of Sydney. Dr. Paul Newman’s primary interests are in mobile robots, and his group is called Mobile Robot Group (MRG) within the larger umbrella of Robotics Research Group at the university.

RESEARCH ACTIVITIES AT OXFORD UNIVERSITY

Activities under Michael Brady

The team met with Michael Brady for about one hour. Prof. Brady talked mostly about Guidance Control System (GCS), the company which he formed after he returned from the United States in 1985. The product line of GCS includes:

a. Marine position sensors, which are designed to aid the automatic positioning of vessels in marine applications.

b. Offender monitoring electronics, which are developed for home detention as an effective, non-custodial alternative to prison.

c. Guided vehicle navigation system, which is primarily used for navigation and control of automatic guided vehicles (AGVs).

According to Prof. Brady, the guided vehicle navigation system has been a very successful product, 700 of which have been installed on the AGV manufactured by FMC Technologies of the United States. Prof. Brady believes that mobile robots will have a great future in a broad scope of applications.

Prof. Brady recently formed another company called Mirada which utilizes his medical image processing technologies. His research is focused on three types of medical images: ultrasound, magnetic resonance imaging (MRI), and mammography. The purpose of the research is for diagnosis and prediction of breast cancers.

Activities under Paul Newman

Dr. Newman’s main interests are in the area of Simultaneous Localization and Mapping (SLAM) for applications in mobile robots, which is a very active topic of study in the United States as well. The ability to place an autonomous vehicle at an unknown location in an unknown environment, have it build a map, using only relative observations of the environment, and then use this map simultaneously to navigate would indeed make such a robot “autonomous.” The SLAM problem has been successfully approached as a
probabilistic problem—inferring position and surroundings from a stream of sensor measurements. A big challenge was in overcoming the scaling problem—how to avoid unbounded growth of computation with map size which prohibits sustainable mobile autonomy. Over the past few years, there has been great progress in this area—mostly by analyzing the underlying inference problem and exploiting its unique structure by application of bespoke estimators.

However the group still does not have SLAM-enabled robots capable of substantive deployments. The problem lies in perception. All the SLAM algorithms require an oracle of some description to associate each measurement with part of the inferred state of the world. If this “Data Association” process goes wrong, terrible things happen. Vehicles get lost, maps get corrupted and new features are mapped when in fact they are re-observing previously seen areas. SLAM algorithms fail catastrophically under poor data associations.

A facet of the research into mobile robotics at Oxford is trying to face the robustness problem head-on. They are combining both sensed geometry, resulting from 2D and 3D laser scanning (see Fig. C.62), and texture information from cameras to extract complex, high-dimensional scene descriptors. They use these rich descriptors to disambiguate the data-association problem, reducing the chances of erroneous measurement-feature pairings and making it easier to solve the “loop closing problem,” recognizing when, contrary to internal location estimates, the vehicle has in fact returned to a previously visited location.

Central to the approach is saliency detection—finding what is interesting and “stands out” in a particular block of 3D laser data or what is remarkable about a given image. Detecting and then later re-detecting saliency in data space (for example by looking at variations in entropy over scale) without recourse to the estimated state (map and vehicle location) offers a substantial increase in robustness.

The research also extends to multiple collaborating millimetre-wave radar sensors for feature detection and multi-spectral SLAM. They are also considering active, high-precision workspace reconstruction using both 3D lasers and cameras for indoor and outdoor settings. A collaboration with the Oxford Department of Linguistics is examining translation between the metric, Euclidian maps of SLAM algorithms and natural language descriptions. This is motivated by the vision of a mobile robot being able to explain and describe its learnt maps to a human user in a natural way. Central to it all is answering “where am I?“ Dr Newman says it is a tough question, but one that needs addressing.
SUMMARY

Oxford University is a reputable organization in robotics research. In recent years, research activities have become more diversified than in the past. Prof. Sir Michael Brady has switched his focus to medical image processing while Dr. Paul Newman, the new academic in mobile robotics research, is focusing on mobile robots with an emphasis on SLAM. In addition to mobile robots, Oxford also studies various topics related to computer graphics, image query, and computer vision. Professor Brady has achieved success in technology transfer, as he has formed two companies. One, called GCS, primarily focuses on sensing and control technologies, and the other is called Mirada, which is in the field of medical images. The latter is relatively new.
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Date: April 29, 2005

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BACKGROUND

Polo Sant’Anna Valdera (PSV) is a research park of the Sant’Anna School of Advanced Studies. The school is located in Pisa, Italy, while the research park is located in a suburban area of Pisa called Pontedera. Founded in 2003, the PSV research park consists of eight laboratories and centers: a. ARTS Lab (Advanced Robotics Technology and Systems Laboratory), b. BIO Labs (Biological Laboratories), c. CRIM (Center for Applied Research in Micro and Nano Engineering), d. PERCRO (Perceptual Robotic Laboratory), e. RETIS (Real-Time Systems Laboratory), f. EZ-Lab Research Center, which focuses on technologies and support services related to longevity, g. IN.SAT (Business and Territorial Systems Innovation Laboratory), and h. Humanoid Robotics Research Center, which is a collaboration program with Waseda University of Japan, established under the scientific-cultural agreement between Italy and Japan. Dr. Paolo Dario, the director of the research park, was our host and introduced two laboratories: ARTS and CRIM, respectively, which was followed by a visit to the two laboratories by the team.

Overall Activities of ARTS and CRIM

The two laboratories have 90 scientists including 15 PhD students. Research activities cover topics from robotic components to systems, aiming to develop four strategic lines:

a. Surgical robots  
b. Mini/micro/nanorobotics  
c. Rehabilitation robots  
d. Assistive technology for elderly people

Activities in each of the two laboratories are described below.

The ARTS Lab

The ARTS laboratory focuses on basic research of robotics, mechatronics and bioengineering. Research projects currently going on explore biomorphic and anthropomorphic solutions for robotic devices in general, and biomechanics, neurorobotics, and rehabilitation and assistive devices in particular. One such project investigates implantable microdevices which can detect neuron signals from human arms to directly control robotic devices. (Fig. C.65)
The second project was a so-called humanoid robot, though it was different from humanoid robots that we had seen, a robot equipped with legs and arms, for example. The one in the ARTS laboratory focuses on eye-hand coordination, which is used to study sensor-motor control mechanism of human beings and its application to robotic arms (Fig. C.66).

The third project was a legged microdevice, which could be used as capsular endoscope. The researchers of ARTS study how such a device can automatically move in a tubular, compliant and slippery environment. The potential application is for the diagnosis and therapy of gastrointestinal tract problems of human beings. The fourth topic is an active microendoscope for exploration of the spinal cord. Another topic is related to a mechatronic tool for computer-assisted arthroscopy.

We also saw two robotic hands with five fingers, one made entirely of silicon based materials and the other of metal components. In both cases, each finger had just one degree of freedom.

**The CRIM Lab**

CRIM focuses on the design and development of micro- and nano-devices, but its strategy is to avoid silicon processing methods popularly used for fabricating integrated circuit (IC) devices which includes many chemical processes such as lithography, itching, diffusion. Instead, CRIM directly cuts materials, plastic, metal or silicon using precision machines. For that purpose, CRIM is provided with a set of machining equipment, such as a Kern HSPC micro computerized numerically controlled (CNC) machine, an electrical discharge machine, a plastic injection molding machine, and a microerosion system. All the equipment is housed in a 100 square meter cleanroom of classes 1,000 and 10,000.
With the above set of equipment, CRIM has developed micro- and nanosensors for different applications including:

a. A novel hybrid silicon three-axial force sensor with a volume less than 7 mm³
b. Environment-monitoring devices such as a microsensor for atmospheric mercury monitoring and microEMS (Micro Environmental Monitor System) for analyzing heavy metal pollutants in surface and ground water
c. Endoscopy, which was mentioned earlier
d. A mechatronic tool for computer-assisted arthroscopy, which was mentioned earlier

**SUMMARY**

The PSV research park was one of the largest groups in robotics research that the assessment panel visited. Robotics research activities are primarily conducted in two laboratories, ARTS and CRIM. Current efforts of PSV focus on four strategic lines: surgical robots, mini/micro/nanorobotics, rehabilitation robots, and assistive technology for the elderly. During the research, however, researchers of PSV seek biomorphic and anthropomorphic solutions. PSV has developed quite a few robotic devices and systems while researchers are equally strong in fundamental studies, as many papers have been published by PSV.

Another note is that PSV has an active joint program with the Waseda University in Japan called RoboCasa for which students were exchanged (the WTEC study team saw three Italian students at Waseda University in late 2004).
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Date Visited: April 28, 2005

WTEC Attendees: R. Ambrose (Report author), M. Dastoor, Y.T. Chien, B. Wilcox, D. Lavery

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BACKGROUND

Prof. Hommel has been working in robotics for more than 20 years, starting at Technical University Munich (TUM) before coming to Technical University Berlin (TUB). He started in computational kinematics, developing an expert system to find closed form solutions for the inverse kinematic problem. Working with the University of Southern California (USC)/Belgrade dexterous hand led to the development of a sensor glove used for teach-in programming and other applications like gesture recognition. For path planning and collision avoidance (and also for parallel robots), first geometric algorithms were used resulting also in work on geometric assembly planning. Later, motion planning problems were solved using methods from optimization theory. For task planning a knowledge-based real-time planning system was realized using modal logic and scripts for knowledge representation. In the field of object recognition, different sensor systems based on ultrasonic 3D field reconstruction, active stereo vision, and lasers were developed. Service robotics (in close cooperation with Daimler-Chrysler), and medical robotics (in close cooperation with Charite University Hospital in Berlin) were more recent activities. Currently, aerial robotics, exoskeletons, and biologically inspired control architectures for mobile robots are the main foci in the field of robotics.

HELI OPTERS

One of the research directions of the group is focused on autonomous helicopters. A huge amount of work has been performed in helicopter control, development of low-cost sensors for autonomous flight, sensor fusion and algorithms for environment perception. The current and future work in this research area is devoted to cooperation of multiple autonomous helicopters for coordinated execution of different tasks, e.g. perception of the environment with different sensors mounted on different helicopters, transport of a load with multiple coupled helicopters.

Figure C.67. Marvin Mark II in autonomous flight.
The first lab was centered on custom helicopter integration using a commercial gas-powered chassis. These helicopters are meant for autonomous outside flying and have a rotor diameter of approximately 2 meters. The helicopter design is the successor of the Marvin helicopter that won the International Aerial Robotic Competition held in the year 2000 by the Association for Unmanned Vehicle Systems (AUVS). In the last three years these helicopters were part of a European project working on the coordination and cooperation of a fleet of heterogeneous unmanned aerial vehicles (UAVs). The team just came back from the final demonstration in a forest fire scenario, which was held in Portugal (see above). The flying system itself nicely integrates all necessary sensors and computational power for autonomous flight and environment perception, namely a camera on a pan-tilt-platform and a special kind of fire sensor in a custom build case (see below). The systems are reported to do fully autonomous start, land and fly 3D trajectories.

In the second lab an experimental setup based on a free-flying autonomous electrical helicopter was developed. This setup is composed of a commonly used electrical model helicopter equipped with a microcontroller and a small size computer with a real-time OS as well as with an inertial measurement unit. The Cartesian coordinates of the helicopter are provided by mechanical linkage connected to the helicopter and to the ceiling. The team is working on a vision-based system which should replace the linkage. With the experimental setup in this lab, real flight experiments can be performed. This setup has been used for experimental validation of new approaches for helicopter control and for experimental validation of the models for helicopter behaviors, especially for the air dynamical effects on the main rotor.
Exoskeletons

The research on exoskeletal devices at the institute is divided into two parts: powered leg orthosis and hand exoskeleton. Whereas the hand exoskeletal work is loosely based on former work of the TUB data glove, the leg orthosis is a completely new project running for almost two years now. The aim of the project is to develop a device that is able to support the leg muscles during common movements like walking, climbing stairs and getting up from a chair—mainly for rehabilitational purposes. With this goal in mind, the main attention is paid to the human-machine-interface that has to be able to recognize the desired motion of the operator to support it properly.

Two approaches to achieve this are currently investigated: 1) Motion recognition by analyzing electromyographic (EMG) signals of the muscles spanning the actuated joint(s). 2) Analyzing the motion of the so-called “healthy” leg and deriving a suitable motion for the supported leg. Additional attention is paid to implementing new control strategies for the actuator control and to improving sensor data processing to get a precise measurement of the current body state and outer influences like (ground) reaction forces through the sensors embedded in the orthosis.
The hand exoskeleton has been developed with the main focus on rehabilitation and diagnostic support. The work is performed in cooperation with the clinic of Ulm University. The robotic assisted rehabilitation is believed to enhance rehabilitation after surgery or stroke. Currently four degrees of freedom for one finger are actuated by the mechanism but the final exoskeleton will support all fingers. Force is transmitted via pull cables to the joints of the exoskeleton. Sensors of the exoskeleton capture position, force values, and muscle activity. Based upon basic position control, more complex modes including force control are under development.
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Date: April 27, 2005

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BACKGROUND

Prof. Dr. Alois Knoll gave a brief introduction to the Technical University of Munich (TUM). The university originally existed as the University of Ingolstadt from 1472. It was moved to the capital of Bavaria, Munich, in the year 1826, by Louis I. Four Nobel Prize winners have been faculty at TUM. TUM has about 20,000 students (both graduate and undergraduate), with 480 professors and 8,500 total employees. It is ranked first in “3rd party” funding in Germany, at about €120 million per year. It has the largest neutron source in Europe (a reactor); it operates the European Southern Observatory in Chile, and has a number of Max Plank Institutes on campus. It is based on three campuses: Garching (with most engineering departments), Freising/Weihenstephan (hosting the “green departments,” agriculture, food technology—and the oldest brewery) and the Munich city center (with electrical engineering, economics, architecture). The mechanical engineering area consists of eight parts including mechatronics, machines and vehicles, and medical technology. In the Informatics area they have 19 chairs, 49 professors, 2,223 students (of which 414 are in their first year. Between 5 and 10% continue to the doctorate level beyond the “Diploma” (M.Sc.).

A presentation on robot learning was given by Prof Dr. Jürgen Schmidhuber. The focus of this area is on recurrent neural networks, optimal universal learners, and Gödel machines. In the area of cognitive robotics
they have built the Cogbotlab (see http://www.idsia.ch/~juergen/cogbotlab.html). This work is in collaboration with Istituto Dalle Molle di Studi sull'Intelligenza Artificiale (IDSIA) in Lugano, Switzerland. There was a discussion of the fact that the Haber-Bosch process (the commercial process to make ammonia fertilizer) has been declared the most influential invention of the 20th century, since it enabled the population explosion by allowing agricultural productivity to expand exponentially. By analogy, Prof. Schmidhuber stated that we are on the verge of a robot population explosion that will be enabled by cognitive robots. To make such robots possible we need to address the ultimate learning problem: how to maximize the expected remaining “reward function” until death. The question is how to maximize, and what is optimal?

An example shown was a reactive robot that learns to find a yellow cup while avoiding running into a wall. The robot has no prior programming to help it know how to drive. For the case of Robocup they have developed a feedforward neural network to predict/plan five steps ahead. A recurrent neural network (RNN) uses feedback to provide internal state. Conventional neural networks are essentially statistics (e.g. Bayes' Theorem), while RNNs are not the same (see http://www.idsia.ch/~juergen/rnn.html).

They are also investigating evolution methods. Evolino is a system that evolves hidden units in a neural network. A simulation was shown of cylinder with small surface actuators that "learns" to reduce drag to a minimum. Some key ideas are the Bayesmix predictor (closely related to Occam's razor, see http://www.idsia.ch/~marcus/idsia/nipsws.htm), the work of Solomonoff (see http://world.std.com/~rjs/1964pt1.pdf), Hutter Universal Induction and Decision Theory.

Next was a presentation on High-Fidelity Telepresence and Teleaction by Prof. Dr. Alois Knoll (see http://www.sfb453.de/) This work is collaborative between Professors Ulbrich, Bauernschmitt, Knoll, Zäh/Reinhart, Diepold, Steinbach, Buss, Walter, Färber at TUM and Hirzinger at DLR. The overall principal investigator is Prof. Dr.-Ing G. Färber, treated as “collaborative research units (SFB453)” with long-term funding, selected by Deutsche Forschungsgemeinschaft (DFG). This is the German Research Foundation, equivalent to the U.S. National Science Foundation, see http://www.dfg.de/en/index.html. The purpose is to get the best people working together for a maximum of 12 years. Approximately 10% of proposals are funded, for a total of between 100 and 120 that are now funded. These proposals are peer reviewed, with a very elaborate selection process, but if selected, they have total budgets of €2–3 million per year, funding between one to four institutions per proposal, for substantial multi-year durations.

There was a discussion of the desire of TUM to incubate new companies (they have an incubator on the Garching campus). Spin-off companies can apply for venture capital provided in part by the state of Bavaria under a variety of different funding schemes. The university also provides or arranges capitalization as well as intellectual property licensing in return for their share of ownership. For patents, their policy is that 2/3 of patent revenues go to the university, and a third to the university employee (inventor).

Prof. Dr. Heinz Ulbrich of the Institute for Applied Mechanics discussed active control for detection of contact by the tips of turbine blades and prevention of future contacts or shutdown. Turbine tip clearance strongly affects turbine efficiency, but of course contact is a major cause of failure. He also discussed a high-performance pan-tilt head for the automotive industry (see http://www.abayfor.de/abayfor/English/_media/pdf/publikationen/infoblaetter/abayfor_bybias_GB.pdf), and high-performance inertial sensing.

Next the biped walker “Johnnie” (Figure B.73) was discussed. This humanoid robot has a 40 kg mass, is 1.8 m tall, and is designed to walk at 2 km/h. It uses 20 Maxon motors with harmonic drives for actuation. The ankle joints are actuated via linear ball screws. The objective is to demonstrate autonomous walking and hazard avoidance. It was developed by two people over five years, starting eight years ago, with a smaller budget than most of the comparable Japanese projects with similar scope and accomplishments. It was originally a cooperative project with neurological researchers investigating hemi-paretic walking, where a stroke on one side of human brain makes it so that physical therapists have approximately 8–10 weeks to re-establish walking or the brain walking functions are permanently lost. Originally, they wanted fast walking, which worked great in simulation. It seemed that it should have been possible to make a fast walking machine with then-current motors, etc. However, it was not trivial to make stable walking gaits. It is not based on the quasi-static zero moment point (ZMP) algorithm (used by most Japanese researchers) or anything like it—Johnnie is a non-linear dynamical system that must be stabilized. They have close
collaboration with the harmonic drive vendors—friction is 30% of energy, and models must be accurate to be able to stabilize the system with this much friction. The actuator torque is 200 Nm for the hips and knees. Each three degree-of-freedom (DOF) hip actuator assembly has a mass of 4.3 kg with four motors. They wanted very sophisticated foot dynamics but didn't achieve that. They feel that they need toes, but don't have them at this time. They still have close collaboration with neurobiologists. There is still a significant problem with fast walking: by comparison insect walking is much simpler than human walking; no one yet knows very well how human walking is controlled, and fast walking is not really feasible right now with conventional methods (e.g. multi-I/O Position Integral Derivative (PID) control) with observers for friction and gravity). Humans do fast walking with less effort than slow walking—not like robots. Johnny I has >50 sensors, about 80 sensor inputs, including six DOF Inertial Reference Unit (IRU) (currently about 80 Hz, need 400–600 Hz) but does not have a high-performance military-grade inertial sensor. It is hard to model elasticity to compute the angular position of the body—the angular position must be known quite accurately (e.g. to compute the projection of the gravity force through the foot) and one cannot compute it solely from the kinematics. The new biped, Johnnie-II, under development, will have about 400 Nm of torque in the hip and knees using the same size motors. The actuators will have a mass of 5.6 kg with three DOF (compared to 4.3 kg for three DOF) at 200% of the mechanical output power. A good human athlete can deliver almost 300 Nm of torque at the hips. Sensor data processing is not fast enough now—they need fast analog to digital (A/D) conversion at sensors. The computers are not fast enough, but the new models are much quicker than the old ones. The main problems have been with the sensors (e.g. sensor failures), bus bandwidth (they were using a CAN bus, but now use a parallel bus), processing in general, and action selection.
of the new high-performance microelectromechanical systems inertial reference units (IRUs). The answer is that they are aware of all of these methods and feel they are doing the right thing within their budgetary constraints.

Autonomy/Automation in Medical Robotics, part of SFB453, was presented by Dr. Knoll. They are developing haptics (feedback of force and touch sensing) for surgery and skill transfer (e.g. an experienced person training an inexperienced person on how the procedure should “feel”). This approach offers tremendous potential for scaling to non-human “sized” situations, improved accessibility, and range of distance, dexterity and speed. An example is minimally-invasive heart surgery—Intuitive Surgical’s DaVinci system is already on market, but has no autonomy, no haptic feedback (vision only), and is very fatiguing. TUM is developing its own minimally invasive surgery system (see Figure B.74), and they are currently evaluating haptic feedback and automating complex manipulation sequences. For example, they are attempting to tie knots as seen in textbooks for surgery. The system is force-reflecting in three axes (e.g. the human operator “feels” the force in x, y, and z, but not in roll, pitch, or yaw). The first system they have built uses three industrial robots with force sensors and surgical drapes, a head-mounted display, and force-reflective hand controllers (the commercial “Phantom” devices). They can plot the gripper trajectories in 3D space to record any operation, and can “playback” knots tied by skilled surgeons. Tests have demonstrated reduced forces on tissues as compared to direct operations conducted by typical human surgeons. Most surgeons have preferred 2X amplification of force back to the haptic interface, to give them a better “feel” for what is going on. They want to be able to automate elementary operations by closing the visual serving gap. This means, however, that full visual scene interpretation is needed, including recognition and reconstruction of the fine suture material. Moreover, for transparent support of the surgeon and seamless transfer of control between the semi-autonomous robot and the surgeon, the system must be able to recognize what phase the operation process is in. The overall goal is to move the surgeon up in the hierarchy of controllers, e.g. to initiate “skills” that are done automatically. They now have a system with four instruments and multiple endoscopes—they are exploring when additional arms are useful. They are also developing new scenarios for the operating theatre in which M surgeons control N robots.

Next Thomas Bock of the faculty of architecture spoke about construction robotics. The greatest portion of the work in this field is going on in Japan, since there is no cheap labor available there. Approximately 400 robotic civil engineering systems have been built since the early 1980s. For example, tunnel boring is fully automated (e.g. there are no people “down the hole” during normal boring and lining operations). There are realistic near-term visions of fully automated road construction. Examples were presented of attempts to perform channelizing of lava flows near volcanoes by automated systems. Automated house manufacture has demonstrated the capability to build one house every 2.5 minutes. In Japan, they make houses that are 85% prefabricated off-site and take four to six hours to assemble on-site. Over 5,000 houses per year are built this way from many different sorts of materials (steel, concrete, wood, etc.).

Early robots for construction failed because they copied commercial construction instead of making it robot-friendly. At TUM they now have a 12 x 12 m space that can make any type of pre-formed concrete wall panels, floor panels, girders, beams, etc. In the case of a floor tiling robot, the observation was made that many universities have made the same mistake in that they have tried to do such tasks in the same way that humans do them. Instead they should make everything robot-oriented. Their system is now able to make one floor each week—completely finished. They have also developed MORITZ, a pipe crawling walking machine (see http://www.amm.mw.tum.de/Research/Research/fzagler_e.html).
OVERVIEW

The University of Zürich Artificial Intelligence (AI) Laboratory is a group of 20–25 PhD students and five postdoctoral fellows directed by Professor Rolf Pfeifer with a mission to understand intelligence, its embodiments and their interactions with the real world. Pascal Kaufmann, a bright young doctoral student, who also happens to be the president of the Student Research Opportunities Program at Swiss Federal Institute of Technology (ETH), represented Professor Pfeifer's group.

GOALS

The AI Lab is strongly based on the work of Rodney Brooks and has three guiding principles:

- Intelligence is derived from organism-environment interactions and is therefore from the need to build physical embodiments and study interactions with the real world
- The body itself can do physical (analog) computation via its interactions with the real world
- Nature and evolution in nature provide basic principles that can be used for intelligent systems

The different projects are derived from two basic premises. First, intelligence emerges through the interaction of the brain, the morphology of the embodiment and its manifestation, and the environment. Second, the laboratory believes in synthetic methodology, the methodology in which we gain understanding of complex systems by building and realizing these systems in the real world.
PROJECTS

Professor Rolf Pfieffer's laboratory has several funded project areas.

1. Collective intelligence: The organization of robots into flocking and swarming formations by processing simple, local rules based on studies of nature.
3. Evolution of artificial cells: The study of the evolution of cells to mimic biological growth.
4. Artificial evolution morphogenesis: The study of animals with different morphologies, and simple rules for organization leading to different morphologies.
5. Neural interfacing: The concurrent study of neurons, pathways in the brain and the perception-action loops in nature and in robotic systems.
7. Locomotion and orientation, biorobotics: The design of biomimetic locomotion systems and the study of perception-action loops in natural systems.

We were particularly impressed by the commitment to wet lab research (culturing neurons on chips, stimulating neural cells of lamprey fish by laser light) and the coupling of this research to the control of robots. The research includes the use of confocal laser microscopy to understand the mapping of efferent signals to actions in the lamprey brain and the synthesis of a neural network that mimics the lamprey brain.

INTERACTIONS WITH OTHER LABS

The lab has a number of collaborative EU projects and an exchange program with Northwestern University. The neural-interfacing work is done in collaboration with the Swiss Federal Institute of Technology at Hönggerberg.
RESEARCH CULTURE

Postdoctoral and doctoral students have a fair degree of autonomy in pursuing their interests and are encouraged to think creatively within the goals and the philosophy established by the director of the research laboratory. Professor Rolf Pfeifer leads an impressive group funded by a wide range of projects and the group’s activities are very synergistic. The research agenda for the laboratory is wider in scope and on a significantly longer time scale than that for similar laboratories in the United States.