Report on the Dagstuhl Seminar on

Modelling and Planning for Sensor-based Intelligent Robot Systems

September 1 – 6, 1996

Rapid advances in sensors, computers, and algorithms continue to fuel dramatic improvements in intelligent robots. Recently, for example, robot vehicles have been installed in public settings to perform such tasks as delivering items in hospitals and cleaning floors in supermarkets. This Dagstuhl seminar was organized by Dr. Robert C. Bolles (SRI International, USA), Prof. Horst Bunke (University of Bern, Switzerland), and Prof. Hartmut Noltemeier (University of Würzburg, Germany) to bring together researchers in this dynamic field. It included 34 participants from 11 different countries (Austria, Brasil, Germany, Hungary, Japan, The Netherlands, Poland, Spain, Sweden, Switzerland, and USA). 30 presentations were made, plus a video session was held to demonstrate the current state-of-the-art of research vehicles. In addition, on Wednesday afternoon, the group took a long hike through the beautiful surroundings of Schloss Dagstuhl.

The seminar covered the wide range of topics associated with this field, including static and dynamic robot environment modelling; multisensor fusion; active vision; knowledge representation for spatial and spatial-temporal reasoning; reactive behavior; motion planning for autonomous vehicles and manipulators; assembly planning and flexible manufacturing; knowledge acquisition and learning for autonomous robots; architectures and implementation; special applications in manufacturing, medicine, space exploration, telerobotics and service robots.

Schloss Dagstuhl offers an ideal setting for meeting new people and discussing the latest ideas. As one participant said, "The meeting was excellent – I enjoyed talking with everyone, the weather was great, and the food and drinks were superb."

Bob Bolles, Horst Bunke, and Hartmut Noltemeier

Contents

On the Sensor-Based Navigation for a Mobile Robot with Uncertainties

Hiroshi Noborio

Many sensor-based navigation algorithms have been aggressively presented in the last decade. However they do not unfortunately have any structure for dealing with many kinds of errors, e.g. sensing, control, and odometry errors. To overcome this drawback, we design a good platform for discussing such errors, and then propose feasible sensor-based navigation algorithms for a mobile robot including errors. All the previous sensor-based navigation algorithms keep three types of convergence schemes of a mobile robot to its goal position. We call these as metric, topologic, and geometric characteristics. Metric and topologic characteristics are based on global properties of a whole world, and a geometric characteristic is based on a local property of each obstacle. In general, the metric and topologic convergences are completely maintained for sensing and control errors, which are usually not accumulated in a practical environment. Thus we can easily design feasible sensor-based metric and topologic algorithms NC-Class2 and NC-Curv1 with a non-contact obstacle following for a mobile root with sensing and control errors. Moreover, since a damage of the geometric characteristic is too small (damages of the others are too big) against an odometry error, we describe a non-contact geometric algorithms NC-Robust* for the robot with all errors. Finally the algorithm's feasibility is completely ascertained under some experimental results by a mobile robot Nomad with a ring of 24 ultrasonic sensors.

Visually Guided Navigation

Jana Košecká

Rich sensory information, robust control strategies and proper representation of the environment are crucial for successful navigation of a mobile robot. We propose a model of the environment which is suitable for global navigation using visual sensing. At the lowest level of the interaction of the robot with the environment we employ visual servoing techniques which facilitate robust local navigation by means of relative positioning. Further we demonstrate how to use these local control strategies in a global setting. The environment is represented in terms of a place graph, where the nodes correspond to places and arcs have associated servoing strategies for moving from one place to another. The global navigation is expressed as a sequence of relative positioning tasks obtainable from the search of a place graph. The proposed model facilitates generation of motion plans which can be executed in a robust manner thanks to the presence of the sensory information in the feedback loop.

Curvature Constrained Path Planning

Jürgen Sellen

One of the basic problems in non-holonomic motion planning is to compute paths of bounded curvature (resp., turning radius) among polygonal obstacles in the plane. We present two new algorithmic approaches to this intensively studied problem.

The first approach is based on the idea to solve intuitively easy problem instances quickly. The intuitive complexity is measured by the "width" $W = |R_c - R|/R$ of the given input instance, where R denotes the desired turning radius, and R_c the supremum of all turning radii for which an admissible path exists. We present an exact decision algorithm with a running time that is polynomial in W and in the input complexity.

The second approach is based on the desire to compute curvature-constrained paths on danger maps, with applications in military flight path planning. Here, we present an approximation algorithm that finds an ε-approximate shortest path on a grid of size $1/\varepsilon^2$ in time $O(1/\varepsilon^3)$.

Towards (Quasi) Real-Time Range Image Segmentation

Xiaoyi Jiang, Horst Bunke

Today range scanners are able to acquire high-resolution and high-quality range images in real-time. However, range image analysis and interpretation in a robust and fast way is still an open research topic. In particular, there is considerable room for improvement in range image segmentation with respect to both quality and speed. This talk reports our efforts to achieve robust and fast range image segmentation. We have developed three algorithms for segmentation of range images into planar surface patches, into planar and curved patches, and edge detection in range images, respectively. Compared to the known methods in the literature, our algorithms are unique in using high-level segmentation primitives instead of the individual pixels. This way we are able to significantly reduce the amount of data we have to deal with. Along with the simple handling of the high-level primitives a fast and reliable segmentation can be achieved. We have tested our algorithms on a large number of real images acquired by three types of scanners with quite different noise characteristics. The segmentation time ranges from one to a few seconds on a Sun Sparcstation 5, dependent on the image resolution and complexity. The robustness of our algorithms is demonstrated by the different types and noise characteristics of the images used in our experiments.

Using Cyclic String Matching to Find Rotational and Reflectional Symmetric Shapes

Josep Llados, Horst Bunke, Enric Marti

Symmetry is one of the shape features that is often used in computer vision.

Some computer vision systems use symmetric-based indexing functions to retrieve images from an image database. Other computer vision applications need to detect the orientation of a shape before it is matched with a model and, if the shape is rotationally symmetric, a specific method has to be developed to find the principal axes of the shape. Symmetry is also useful to recover a planar symmetric figure from an image without the need of models. In this paper, a simple and fast method to detect perfect and distorted rotational symmetries of 2D objects is described. The boundary of a shape is polygonally approximated and represented as a string. A key observation is that the boundary of a rotationally symmetric shape consists of a sequence of identical substrings. Rotational symmetries are found by cyclic string matching between two identical copies of the shape string. The set of minimum cost edit sequences that transform the shape string to a cyclically shifted version of itself define the rotational symmetry and its order. Finally, it is observed that it is possible to find out if a shape string is reflectionally symmetric by computing the cyclic string matching between the string and a reversed version of itself. Thus, a modification of the algorithm is proposed to detect reflectional symmetries.

Current Research Efforts in Function-Based Recognition

Louise Stark, Melanie Sutton, Kevin Bowyer

The premise of our most recent work is that a recognition system can and should incorporate both the symbolic labeling of the potential functionality of an object and the steps to confirm said functionality through interaction. Hence, the task at hand is as follows. A researcher selects an object and places it in the observation area of a robot arm. An initial intensity and range image are acquired. This initial state is the input to a two-stage recognition system which first performs the symbolic labeling of the object's potential functionality and produces a plan for interaction for the object. The second stage involves the interaction tests, guided by the plan for interaction, to confirm the object's functional task.

Classifying and Recovering from Sensing Failures in Autonomous Mobile Robots

Robin R. Murphy and David Hershberger

The transfer of autonomous mobile robot (AMR) technology to applications in manufacturing, defense, space, and search and rescue have been impeded by a lack of mechanisms to ensure robust and certain sensing. Our research has focused on characterizing sensing failures in AMRs and developing a methodology for classifying and recovering from them. This work has been demonstrated on two mobile robots performing landmark navigation. The approach exploits the ability of the robot to interact with its environment to acquire additional information for classification (i.e., active perception). A Generate and Test strategy is used to generate hypotheses to explain the symptom resulting from the sensing failure. The recovery scheme replaces the affected sensing processes with an alternative logical sensor. This approach is implemented as the Sensor Fusion Effects Exception Handling (SFX-EH) architecture.

Visual Navigation for DARPA's Unmanned Ground Vehicle

Bob Bolles, Martial Hebert, Larry Matthies

Brief descriptions of visual feedback techniques to support the Unmanned Ground Vehicles are presented. The supported behaviors include teleoperation, road following, hillcresting, turn around, tilt-roll refinement, obstacle detection, local path planning, and global path planning. Emphasis is placed on stereo sensing, obstacle detection, and local path planning. Both explicit and implicit obstacle detection techniques are presented. Explicit techniques analyze disparity images or local terrain maps and look for geometric configurations that correspond to obstacles. The explicit techniques look for both "positive" obstacles, which stick up above the ground, and "negative" obstacles, which protrude down below the ground, such as ditches and ravines. Implicit techniques simulate the driving of the vehicle over the local terrain map and look for unstable positions or places where the vehicle is "pierced" by terrain features. The integrated system is demonstrated driving across relatively open fields, avoiding trees, rocks, and ravines.

Using Tabu Search to find Optimal Grasps in Scenes represented by Triangles

Frank Ade

Up to now tabu search has been virtually unknown in the fields of computer vision and robotics although it is used with great success since more than ten years in Operations Research applications. In our contribution we show that tabu search is capable of finding optimal grasping configurations for a two-fingered gripper when the scene is represented by a tessellation of its 3D surfaces into triangles. While most of the general framework of Tabu Search is applicable, some adaptations to the problem at hand have to be made. This concerns mainly the objective function which describes the quality of the grasps. Torques and forces at the fingers have to be considered as well as surface normals and curvatures at the points of contact. Six such local features have been identified and combined (with appropriate weights) into a local quality function. The whole tabu search module was used in a robot system which had the task of removing unmodeled objects from a heap - one by one.

Fixture Design

A. Frank van der Stappen, Mark Overmars, Chantal Wentink

Manufacturing and assembly processes often require objects to be held in such a way that they can resist all external wrenches. The problem of fixture planning is to compute, for a given object and a set of fixturing elements, the set of placements of the fixturing elements that constrain all finite and infinitesimal motions of the object. We extend the set of commonly used fixturing elements with so-called edge fixels, which contact a polygonal object either at a vertex or along an edge of its convex hull. We show that any polygon without parallel edges can be fixtured by a single edge fixel and two point fixels, and that any convex polygon without parallel edges can be fixtured by two perpendicular edges and a single point fixel. Besides some additional positive results, we point out some open problems on fixturability with edge fixels.

Modular fixturing toolkits offer the advantage of reusabilty of the fixturing elements and have therefore gained considerable popularity. A modular fixturing toolkit consists of a fixturing table with a rectangular grid of holes, and a set of fixturing elements whose placements are restricted by the grid. Several recent publications in the field of fixture planning discuss the problem of finding all modular fixtures of a part using a given toolkit. We translate the problem of computing all modular fixtures involving edge fixels into geometric searching problems and present efficient algorithms for some of these problems. In addition, we point out some open problems of algorithmic nature.

Circuit-theoretic Module-based Modelling and Control of Robotic Systems

Suguru Arimoto

Four important issues in modelling and control of robotic motions are pointed out, which are 1) physical scales of the concerned robotic system: length, mass, inertia moment, and time scale (velocity), 2) interaction with an object or the environment (contact force and friction), 3) effect of the use of gears with high reduction ratios, and 4) discontinuity caused by impact (at the velocity level) or static and Coulomb frictions (at the acceleration level). It is shown that robot dynamics can be expressed equivalently by a non-linear position-dependent circuit consisting of circuit modules as extensions of electric circuit elements. Then, the first three issues can be treated through such a circuit by input-output passivity which is an extended notion of impedance. Discontinuity caused by static and Coulomb frictions can be coped with by construction of special circuit modules. This suggests a proposal of inertia-only (gravity/friction-free) robots, whose motions are subject to only the law of inertia.

Ecological Robotics: A Schema-theoretic Approach

Ronald C. Arkin

The goals of this joint research project with ITAM in Mexico City are to provide an understanding and means by which fielded robotic systems are not competing with other agents that are more effective at their designated task; are successful competitors within the ecological system and capable of displacing less efficient agents; and are ecologically sensitive so that agent environment dynamics are well-modeled and as predictable as possible whenever new robotic technology is introduced. Initial studies on neuroscientifically derived schema models of the praying mantis and frog are reported that are leading to both simulation studies and robotic implementations that can provide guidance to neuroscientists, ethologists, and roboticists alike.

Distance Signatures: Distributed Spatial Relations

Erwin Prassler

Typically, relations between an ensemble of spatial objects are described by primitive relations involving the relative position and distance between pairs of geometric entities such as points, lines, or planes. These relations are easy to compute and manipulate, they are very compact, and they provide a simple but efficient tool to describe configurations of spatial objects. A necessary condition for their use is that the objects can be described in an analytical manner, for example by algebraic or semi-algebraic equations, and also that a number of reference features can be named between which the relations are established. The use of such relations becomes questionable if the object descriptions are not available as geometric models but have to be extracted from noisy sensor data.

In this paper we introduce the notion of *distributed spatial relations*. This type of relations is neither restricted to algebraically describable objects nor does it refer to specific geometric reference feature, such as corner points, lines, or planes. Distributed spatial relations are based on artificial force fields. Each object emits a force which can be sensed by the other objects in the ensemble. The force at a specific point in such a field is a function of the distance of the point to the nearest point on the surface of the object which creates the field.

A relation between two objects A and B is encoded in the forces created by object A along the surfaces of object B and vice versa. If the force field is implemented as a grid of discrete distance values, where each grid element is associated with a natural number approximating the Euclidean distance to the nearest surface point of the creating object A, then the forces sensed along the surface of B manifest themselves as a sequence of discrete distance values, which we denoted as *distance signature*. The core idea of distributed spatial relations is that the set of distance signatures created along the surface of an object by the surrounding objects allows one to uniquely identify the object from various views.

In a first experiment, the approach was applied to a set of 2D local range images. In spite of the noise inherent to these images and in spite of the fact that the visibility to the object contours changed from image to image, it was possible to identify a set of object contours over a sequence of such local range images. The method failed when the overlap of the visible contour of corresponding objects became too small and when the object which was to identify was not covered by the distance field from at least three neighboring objects and therefore could not be represented by at least three distance signatures.

Probabilistic Grid-Based Models for Robot Perception, Navigation and Experiment Planning

Alberto Elfes

This talk reviews the application of probabilistic grid-based models and Bayesian estimation procedures to a variety of problems in autonomous robot perception and navigation. The Inference Grid, a stochastic multi-property lattice model, is used to encode the robot's knowledge of the world in a spatially distributed form. Various information metrics are used to determine the extent, accuracy and complexity of the robot's world model, as well as to quantify the information needs of the robot's tasks. A dual control approach allows us to develop a uniform and integrated approach to robot planning and decision-making that takes into account task-related information needs, the perceptual capabilities of the robot, robot knowledge metrics and the spatial characteristics of the environment. We then show how this approach can be used by a mobile robot to autonomously plan and execute experiments that allow it to purposively acquire the information required to solve complex tasks. Finally, we discuss the generalization of the dual control model to a multi-level layered replicated architecture that has been applied to real-time robot systems.

Figures in the Plane

Franz Aurenhammer, Oswin Aichholzer

A novel type of skeleton for general polygonal figures, the straight skeleton $S(G)$ of a planar straight line graph G, is introduced and discussed. Exact bounds on the size of $S(G)$ are derived. The straight line structure of $S(G)$ and its lower combinatorial complexity may make $S(G)$ preferable to the widely used Voronoi diagram (or medial axis) of G in motion planning applications. We explain why $S(G)$ has no Voronoi diagram based interpretation and why standard construction techniques fail to work. A simple $O(n)$ space algorithm for constructing $S(G)$ is proposed. The worst-case running time is $O(n^2 \log n)$, but the algorithm can be expected to be practically efficient, and it is easy to implement.

We also show that the concept of $S(G)$ is flexible enough to allow an individual weighting of the edges and vertices of G, without changes in the maximal size of $S(G)$, or in the method of construction. Such weighting schemes might be used to design a path that keeps the robot away from dangerous edges or sharp angles in the workspace. A completely different application of $S(G)$ concerns the reconstruction of a geographical terrain from a given river map, and to the construction of a polygonal roof above a given layout of ground walls.

Motion Planning in Realistic Environments

Knut Verbarg, André Hensel

We investigate the problem of constructing a *shortest path* of a point–like robot between two configurations in the Euclidean plane cluttered with (intersecting) convex polygonal obstacles. One common approach is to construct the *visibility graph* (VG) and search within this graph in a total time of $O(n^2)$. We show that in general it is not necessary to construct the entire visibility graph. In contrast, we develop two hierarchical motion-planning techniques based on the *monotonous bisector tree* and the visibility graph, which are shown to be more efficient in scenes of *low object density.* In our setting the visibility graph can be *incrementally* constructed in time $O(n^2 \log n)$, where n is the complexity of the scene. A shortest path can then be constructed in time $O(l^4 \log l + n \log l)$, if a shortest path of length l exists. The dependency on n can be further reduced by the use of a spatial data structure to $O(l^4 \log l + l^2 \log l \log n)$. If l is not small compared to the diameter D_S of the scene, the algorithm still respects an $O(n^2(\log n + \log D_S))$ upper bound. If no path exists, then similar estimations for the diameter of a set of obstacles certifying the failure can be stated. We report on experimental results verifying the efficiency of the methods.

We then show that a shortest path under the same assumptions can also be found very elegantly by applying the A* algorithm to the visibility graph. Instead of constructing the graph we compute the visible vertices on-line as soon as they are visited by the algorithm. This can be accomplished by constructing the visibility polygon with the help of Davenport-Schinzel sequences and an iteration like the ellipse method in time $O(M^2 \log M \log Mn)$, where M is the diameter of the visibility polygon. Plugged into the A* algorithm we obtain a total running time of $O(l^4 + l^2 \log(l + M) + l^2M^2 \log M \log Mn)$ if a shortest path of length l exists.

Finally, we extend the ideas to general motion planning problems with f degrees of freedom. The basic ingredients are solely the computation of the *clearance* of the robot in the workspace and a vector compiling the geometry of the robot, which makes the method applicable in many different situations. The setting is motivated by welding robots of Audi AG. The idea is to explore the free space starting at one configuration guided by the A* algorithm. To prevent from reentering already known parts of the free space, we always have to check all nodes to be expanded with this respect. This can be done very efficiently by a spatial data structure since the L_1-like balls modelling our approximation of the free space obey certain properties. We report on experimental results for different types of robots and manipulators showing that a “safe” path can be efficiently found if a path with large clearance exists.

Distributed Control of Microrobots for Different Applications

Thomas Laengle, Joerg Seyfried, Ulrich Rembold

During the last years, the need for large and complex technical systems has become obvious. Examples are manufacturing cells, transport systems consisting of many vehicles, or robots working together to reach a common goal. As a consequence, the control architectures for these systems are not longer able to guarantee the well known properties of modularity, fault-tolerance, integrability and extendibility. On that account, the former centralized architectures are often replaced by distributed control mechanisms.

During the last three years, the University of Karlsruhe has developed an infrastructure for distributed robot systems. This way, the problems of communication, coordination and cooperation between the system components, the task allocation, optimization and deadlock-avoidance are managed by the architecture KAMARA (KArlsruher Multi Agent Robot Architecture) itself. Using these concepts, the planning system for the Karlsruhe Autonomous Mobile Robot KAMRO was realized in a very short time.

To prove the general use of the infrastructure, the control architecture for the microrobots MINIMAN is being developed at IPR by use of these new concepts. One robot consists of two manipulators driven by three piezoactuators, and it can move by use of three piezolegs. In the application field of these robots (medicine, biology and chip production), it is often necessary that the microrobots cooperate to perform difficult tasks. Due to the complexity of the system, the interactions between the robots, and the possibility of dead-locks during the task allocation, the KAMARA architecture was used to solve these problems in an efficient way. In this talk, the results of the work and some experiments with the new system are described.

Distributed Control of Mobile Robots

Ichiro Suzuki, Masafumi Yamashita

Consider a system of multiple mobile robots in which each robot, at infinitely many unpredictable time instants, observe the positions of all the robots and moves to a new position determined by the given algorithm. The robots are anonymous in the sense that they all execute the same algorithm and they cannot be distinguished by their appearances.

In this talk, we discuss a number of problems related to the formation of geometric patterns in the plane and agreement on a given concept by the robots.

Multi-Robot Cooperative Monitoring of Multiple Moving Targets

Lynne E. Parker

An important issue that arises in the automation of many large-scale security, surveillance, and reconnaissance tasks is that of monitoring (or observing) the movements of targets navigating in a bounded area of interest. A key research issue in these problems is that of sensor placement — determining where sensors should be located to maintain the targets in view. In complex applications of this type, the use of multiple sensors dynamically moving over time is required. In this paper, we investigate the use of a cooperative team of autonomous sensor-based robots for multi-robot observation of multiple moving targets. We focus primarily on developing the distributed control strategies that allow the robot team to minimize the total time in which targets escape observation by some robot team member in the area of interest. Our initial efforts in this problem address the aspects of distributed control in homogeneous robot teams with equivalent sensing and movement capabilities working in an uncluttered, bounded area. This paper first formalizes the problem, then shows that it is NP-hard. We then present a distributed approximate approach to solving this problem that combines low-level multi-robot control with higher-level control. The low-level control is described in terms of force fields around the targets and the robots. The higher level control is presented in the ALLIANCE formulation. We then present the results of the implementation of our approach, both in simulation and on physical robots.

Types of Cooperation in the Distributed Robot System CoMRoS

Alexander Rausch, Paul Levi

Robots operating in the same environment share common driving space. Based upon a hierarchical road network we describe the different stages of cooperation that are occuring in the distributed robot system CoMRoS. Asynchronous cooperation arises if preplanned trajectories of autonomous mobile robots with individual goals overlap. Synchronous cooperation takes place if several robots coordinate their actions in order to fulfill a collective task. We concentrate on all effects that result in the course of intersection passing. If a robot intends to pass through an intersection and its destination road is blocked by another robot then the first robot must not enter the intersection. In case of cyclic dependencies the involved robots are faced with a deadlock situation. After deadlock detection the robots organize themselves to constitute a vehicle formation. The robots recover from deadlock by moving along the directions of the dependency cycle until each robot has reached its predecessor's former configuration. While intersection passing in in its regular form is an example for asynchronous cooperation deadlock handling shows cooperative synchronous behavior.

Environment Modelling without Interpretation

Ewald von Puttkamer

A robot is described which represents its environment by a net of typical sensor situations. All sensor readings of the robot (light intensities, tactile readings and position) taken at a time are condensed into a vector, the sensor situation. They are checked against typical situations taken thus far. If the sensor situation is near a typical one, this is shifted towards the new reading. If it is far off any other it is taken as a new typical situation itself. A vertex is drawn between the last typical situation seen and the current one. A visiting counter is incremented for this vertex while the corresponding counters for all other vertices emanating from the last typical situation are proportionally decremented. A visiting counter is attached to each typical situation and incremented every time this situation is the nearest typical one for a given sensor input. If the counter exceeds a preset value the input is taken as a new typical situation. If all vertex counters to a typical situation become zero this node is eliminated from the graph. Drift effects are compensated going back into well known regions once n a while. Sorting the typical situations according to their position in space limits the search effort to find the best matching typical situation for a given sensor situation. The graph represents the environment of the robot and allows navigation through the environment.

General Visibility

Heinrich Müller

Visibility is a key issue in robotics. For example, many sensors cover regions which are within the range of what can be seen from the sensor. Thus, for computational simulation of sensor based behavior of mobile robots, efficient treatment of visibility is crucial.

We present a technique for representing visibility within geometric scenes in a comprehensive way. The representation saves two dimensions against the straightforward representation of visibility by viewing line segments which needs a dimension of 2d for a scene of dimension d. Thus for a 3d-scene, only 4d visibility spaces are necessary which brings the approach down to practicability.

The representation is used for a data structure called hierarchical blocker tree which allows for efficiently reporting the visibility between two arbitrary query sets, and for efficiently finding all scene elements visible from an arbitrary query set. The practical implementation is based on quadtrees, and intersection, union, and difference of quadtrees are the basic operations for constructing and querying the hierarchical blocker trees. An implementation in flatland shows a promising behavior.

Technology Requirements for Advanced Service Robots

Wendelin Feiten

The first generation of service robots has now reached a stage where their introduction is more a question of the market than of the technical feasibility. The first application domains are transport in in-door environments like e.g. hospitals and floor cleaning in the commercial sector. Building on these first applications, the next generation of service robots will need manipulation in order to significantly enhance the domain of competence. In transportation this would be the ability to autonomously open and close doors in order to get into rooms, and autonomous loading and unloading of a well defined set of objects, like e.g. mail folders or meal trays. In cleaning, this would be the ability to clean other objects than the floor, e.g. sanitation cleaning. In order to manipulate in an everyday environment in such a fashion, in addition to navigation and obstacle avoidance of the mobile base, the following basic functionalities will have to be provided: object identification, localization and approach, grasping of the object and obstacle avoidance of the robot arm. For the implementation of these basic functionalities, the suitedness of different approaches is assessed: ultrasonic sensors, vision sensors – monocular with motion stereo as well as binocular or multi-baseline-stereo, structured light, 2 and 3-D laser scanners, servoing in feature space and based on geometrical models and tactile sensing. Furtheron, the basic functionalities and the corresponding hardware are rated with respect to their priority, the state of the corresponding research and the intensity of the research.

Integration of Automated Guided Vehicles in Transporting Plants

Christian Zirkelbach

AGVs are an useful alternative to fixed conveyor systems and able to cooperate with stationary transporting systems. Using a Supervisor Administration System it is possible to integrate the AGV-System into a complete transporting system and to provide a save traffic control, even if the vehicles have only poor behavior. To control the traffic the supervisor needs to operate like a database for the resources (crossings, docking-stations, doors, ...). In this context the blocking-techniques known by operation research methods can be widely improved means by using geometrical features and the properties of the vehicles. Of course you still have to handle difficult maneuvers. This can be achieved means by a manual teach-in-process. Equipped with a set of teached in maneuvers and under the guide of the supervisor even high speed vehicles are able to cooperate.

The disadvantage is a high communication effort between the supervisor and the vehicles, which bounds the maximal number of vehicles. Now the goal is to make more use of the sensory input and to increase the behavioral properties of the single vehicles in order to reduce the administration effort of the supervisor.

Acquisition of Elementary Robot Skills from Human Demonstration

Rüdiger Dillmann, Michael Kaiser

Transferring elementary skills to robots by means of demonstrations is a very intuitive approach to robot programming. Within this paper, we develop a model of skill acquisition that is based on both the nature of elementary skills, the characteristics of real robot systems, and the role of the human user, who acts as a teacher. This model describes skill acquisition as a process consisting of several phases that must all be adequately supported. We present methods and algorithms that allow automation of most of theses phases, such that the involvement of the human user can be limited to the initial demonstration at the beginning and the high-level evaluation at the end of the process. The whole approach is related to human skill learning. Examples for the acquisition of both manipulation and navigation skills are given. Finally, the strengths and limitations of the demonstration-based approach in general are discussed.

Dynamic Systems for Navigation

Henrik I. Christensen, Edward Large, Ruzena Bajcsy

Recently there has been an increased interest in behavior based robotics, where individual behaviors couple perception and action, while more complex behaviors are generated through composition of simple ones. In general a rather limited mathematical basis has been applied in the design and analysis of such behavior based systems. Through adaptation of the paradigm of 'dynamic systems' it is however, possible to provide a basis that facilitate structured design and analysis. To accommodate implementation of such systems it is, however, necessary to incorporate methods for resolution of conflicts and methods for memory management.

In this talk the use of dynamic systems for robot navigation is introduced and an in-depth description of methods for behavioral competition is provided. In addition the notion of a horizon is used for introduction of a mechanism that enable adaptive selection of map size or sensor planning. The operation of a real robot is demonstrated and a MATLAB toolbox for navigation using dynamic systems is outlined.

Planning under Stochastic Conditions

Thomas Kaempke

Sensor information is investigated for non-immediate use by an idealized robot in a varying environment. Long term behavior follows a dynamic program. The relations between sensor data that matter for a given task are formulated by a Bayesian inference network which is algorithmically constructed. The construction can be based on entropy or on distance measures. The induced Markov field serves for computing transition laws of the dynamic program.

Greedy Robot Localization in Simple Polygons
Sven Schuierer

The problem of *localization*, i.e. of a robot finding its position on a map P, is an important task for autonomous mobile robots. From its initial position p, the robot sees its immediate surroundings or *visibility polygon*. Since there may be several positions or *placements* in P that have the same visibility polygon as p, the robot has to move around and use range sensing to determine its position. We say that the robot employs a *localization strategy*. Localization strategies have applications in numerous areas of robotics ranging from aerial photography to autonomous vehicle exploration.

A simple localization strategy that follows the greedy principle is to repeatedly go to the closest point at which at least one placement can be eliminated. If P is a simple polygon with n edges and there are initially k placements, then the previously fastest implementation of Greedy Localization runs in time and space $O(k^2n^4)$. We show how Greedy Localization can be implemented in time $O(kn \log n)$ and space $O(kn)$.

2D and 3D World Modelling using Optical Scanner Data
Piotr Skrzypczynski

Navigation is the fundamental requirement of an autonomous mobile robot. This task requires to automatically build a model of an unknown environment. This internal world model (map) should be created using data delivered by external sensors of the mobile robot.

A system to build a world model of an unknown indoor environment is presented. Solutions are proposed for building either 2D or 2.5D world models. Both models are based on three kinds of geometrical primitives: polygons, polylines and clusters. Polygons are used to model 'closed' obstacles like boxes; polylines model 'open' obstacles like walls, and clusters represent sets of measurements which can not be represented as any other primitive. These models can be used for either planning, localization or obstacle recognition purposes. The models are built up using data obtained from a three-dimensional optical scanner mounted on the autonomous mobile robot.

The emphasis of this work is on the representation of the complex objects (obstacles) and on the integration of primitives from multiple scans. Algorithms for edge detection and matching are presented. Methods for complex obstacle reconstruction from line segments are given. Method which allows automatic determination of needed number and configuration of layers in the 2.5D map is presented.

Results of simulations and experimental runs in real indoor environment are provided. Experiments have shown that the algorithms are able to yield the world model in real time. The quality of the resulting world models will allow the mobile robot to use them for path planning purpose.