Horst Bunke, Takeo Kanade,
Hartmut Noltemeier (editors):

Environment Modelling and Motion Planning for Autonomous Robots

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Tel.: +49-6871 - 2458
Fax: +49-6871 - 5942

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Bezugsadresse: Geschäftsstelle Schloss Dagstuhl
Universität des Saarlandes
Postfach 15 11 50
D-66041 Saarbrücken, Germany
Tel.: +49 -681 - 302 - 4396
Fax: +49 -681 - 302 - 4397
e-mail: office@dag.uni-sb.de

Report on the Dagstuhl Seminar on

Environment Modelling and Motion Planning for Autonomous Robots

October 24 – 28, 1994

This Dagstuhl seminar was jointly organized by Professors Horst Bunke (University of Bern, Switzerland), Hartmut Noltemeier (University of Würzburg, Germany), and Takeo Kanade (Carnegie Mellon University, Pittsburgh, PA). It brought together 34 participants from 10 different countries (Australia, Austria, Denmark, France, Germany, Japan, The Netherlands, Spain, Switzerland, and USA). A total of 31 presentations were given.

The topic of the seminar was of interdisciplinary character addressing problems from different areas such as processing and interpretation of sensory input; multisensor fusion; active vision; static and dynamic robot environment modelling; motion planning for autonomous vehicles, robot arms, end effectors; reactive behavior; knowledge representation for spatial and spatial-temporal reasoning; knowledge acquisition and learning for autonomous robots; architectures and implementation; special applications in manufacturing, medicine, and space exploration. All talks were accompanied by lively discussions. A video session with impressive demonstrations of the state of the art in robotics research was held on the evening of Tuesday, October 25. An excursion to Trier was organized on the afternoon of Wednesday, October 26.

All participants took great benefit from the presentations and the exchange of ideas. Also, many new contacts were established during the seminar. Schloss Dagstuhl with its superb facilities was an ideal location that greatly contributed to the success of the seminar.

Host Bunke, Hartmut Noltemeier, and Takeo Kanade

Contents

Grasping Unknown Objects

Frank Ade

In our project "Dealing with Unknown Objects" we are investigating the problem of removing unknown objects from a scene with the help of a stationary robot arm. There are no stored models of these objects and the recovery of the objects relies exclusively on geometric information. The use of range data thus is a natural choice. As the objects are to be grasped with a two-fingered gripper it is mandatory that the system can see opposite faces. Therefore two range views from opposite sides are acquired and analyzed. We have succeeded in integrating the range data from the two views in a consistent way. Other accomplishments of the project are: controlled approximation of the surfaces in the scene by planar patches, creation of a representation of the scene which is rich enough to support segmentation of it into object hypotheses and the determination of grasps. We have built a complete system - from data acquisition to action.

A Nonlinear Circuit Theory for Physically Understanding Dextrous Robot (Human) Motions

Suguru Arimoto

A class of nonlinear circuits is introduced in order to present a physical understanding of dextrous motions of nonlinear mechanical systems such as robotic arms and hands. A circuit is composed of blocks called 1) resistor, 2) virtual resistor, 3) kinetic inductor, 4) gravity capacitor, 5) displacement capacitor, and 6) current or voltage source. Through each block a velocity vector of n-tuples flows into and out of like an electrical current and a corresponding vector of voltage drop arises between the input and output terminals. Except the current or voltage source each block can be interpreted as a nonlinear position-dependent operator on a domain of velocity vectors. Both Kirchhoff's current and voltage laws are valid, which correspond to d'Alambert's principle concerning of the balance of forces. A few examples for set-point control problems of nonlinear mechanical systems are analyzed to show the effective use of such nonlinear circuits in design of controllers. Further a long standing problem of robot control concerning the globally asymptotic stability of PID feedback without gravity force compensation has been solved by means of direct-current analysis of a special nonlinear position-dependent circuit.

Local Environment Modeling Through Integrated Stereo and Motion Analysis

Robert C. Bolles, H. Harlyn Baker

To illustrate the current state of the art in environment modeling we briefly describe two robots and outline their representations, sensing systems, and path planning techniques. The first robot is Flakey, an indoor robot that uses sonar and realtime stereo to navigate through rooms and follow people. The second robot is the Unmanned Ground Vehicle, an outdoor robot that uses LADAR or stereo ranging to detect obstacles on roads and in fields.

To improve the obstacle detection capabilities of these systems, we have developed a spatiotemporal integration technique that produces range images that have both higher resolution and fewer errors than the range results produced by conventional techniques. Our approach is to apply multiple "structural" consistency checks over space and time to filter out mistakes, instead of applying smoothing-type operations that reduce resolution.

We are currently developing an efficient technique for computing the path of a stereo pair of cameras from a sequence of their images. This set of 6-degree-of-freedom transformations will provide the information necessary to construct and refine three-dimensional environmental maps over time.

Model-Based Multisensory Robot Vision

Horst Bunke, Xiaoyi Jiang

A multisensory vision system is presented that is intended to support the vision requirements of an intelligent robot system. Contrary to many other vision systems, our system has two significant new features. First, it contains multiple sensors, object representations, image analysis and interpretation methods in order to solve a number of different vision tasks. Secondly, it includes a vision planner. Upon receiving a task-level command from the host robot system, the vision planner transforms it into an appropriate sequence of vision operations, executes them, and tries to find alternative vision operations in case of failure. Experimental results demonstrate the advantage of this combination of multiple resources with the vision planner in solving various vision tasks.

Infrared Image Understanding

Claude Caillas

One of the important issues in low level vision consists in recovering physical properties of objects from images. A lot of work has been done in the past for recovering both reflectivity and shape of objects from intensity or color images. In this article, we deal with infrared thermal images that are much less studied than classical ones.

Our goal here is to recover physical properties of objects, such as reflectivity, emissivity and thermal inertia from the analysis of infrared thermal images in outdoor scenes. Our approach is based on the extensive use of the physical laws that are at the origin of the formation of the image. First, we derive a physical model that describes how planar and horizontal surfaces appear in infrared images. A numerical modeling, taking into account meteorological parameters, is presented in order to calculate intensity pixel in the image as a function of physical properties of materials. The calculation of the intensity pixel is performed for every possible combination of material properties. Second, we inverse the physical model by using a least square fitting method; this method looks for the modeled intensity pixel that best matches the experimental one given by the camera.

Applying this method to an experimental scene composed of several kinds of sand lead to reasonable results. Although reasonable, these results are not perfectly reliable due to the non-linearity of the model. We demonstrate that the solution of the problem is not unique. A given thermal behavior of objects can come from different sets of physical parameters bound within some relations of "invariance". We then show that one can obtain more reliable results by taking advantage of these relations of invariance.

Autonomous Navigation

Henrik I. Christensen

For a rich variety of tasks ranging from simple cleaning to delivery and exploration it may be advantagous to engage mobile platforms. A prerequisite for use of such platforms is, however, the availability of a suite of sensor/perception modules that enable robust interaction with the environment.

In this presentation an initial system for autonomous mobile navigation is outlined. The system has been designed with particular emphasis on robust operation in a natural environment, in this case an office/laboratory setting. The presentation outlines the architectural and control considerations that formed the basis for the system. Subsequently the set of 'purposive' modules used for map generation, landmark recognition and reactive interaction with the environment is outlined. It is then described how the modules are interfaced to a real robot, and how procesisng is coordinated to achieve autonomy. Finally the results from a set of experiments are summarised and a set of issues for future research are outlined. This part of the presentation is complemented by a video showing the robot operating in a laboratory setting, where is performs delivery tasks.

Learning Reactive Behaviour for Autonomous Mobile Robots

Rüdiger Dillmann

Autonomy for robot systems requires the capability to plan, react, execute and monitor actions in regard to reach a given goal or to fulfill a task or a mission. Thus the system has a need for a set of strategic, tactic and reactive knowledge to perform the task. In addition self organizing capabilities are required in order to make use from experience from the past in order to do current or future tasks better. From AI research machine learning methods have been proposed which may be useful. Induction is considered to be useful, whether symbolic or subsymbolic. To illustrate how to use machine learning strategies for robots the system PRIAMOS is outlined, which is able to learn knowledge about the environment, task knowledge, skills and reactive knowledge. The problems of learning, results and future potential applications are discussed. Autonomous systems may learn by training, interactive tutoring or by discover. However, learning components are supplemented modules, which have to be integrated into existing systems. Some architectural approaches will be discussed.

Object Recognition as a Discrete Control Problem

Bruce A. Draper

Computer vision technology has advanced greatly over the past twenty years, with particular progress being made on well-defined subproblems such as edge detection, pose determination and structure-from-X. In general, these advances have come when researchers shared a common framework for discussing a problem, and were able to express their assumptions, algorithms and results clearly and mathematically. This allowed researchers to extend each others work, or to pursue clearly-stated alternatives based on different assumptions and/or with different computational costs. This has lead to progress according to the standard scientific model, where steady improvements in solution techniques arise from extensions of (and comparisons with) previous work.

Unfortunately, comparatively little progress has been made on the general object recognition problem, in part because there is no consensus as to a problem statement or solution framework. This has made it difficult to evaluate most object recognition systems, or even to get a concise statement of their assumptions and results. Consequently, few object recognition researchers have built upon each others work, and the study of object recognition has failed to create the same type of competitive synergy that has advanced our understanding of other problems.

In this paper, we consider how object recognition systems might be described succinctly and mathematically. Although the term "object recognition" is used to refer to a wide range of problems, we concentrate on the (visual) search problem: given an object class, find an instance of the class in a scene. Examples of visual search problems include landmark recognition, military automatic target recognition (ATR) and content-based retrieval problem. The defining property of a visual search problem, present in all of these examples, is that the target object class is fixed, and the data that must be searched for instances of the target class. Visual search is therefore the inverse of the labeling problem, where the (presegmented) data is fixed and it is the object database that must be searched for a match.

What makes visual search such a seemingly intractable problem are the variations within object classes. Any formalism for object recognition must admit our standard, intuitive notion of object classes. This includes common yet difficult to model objects such as chairs, human faces and trees, as well as simpler (and better modeled) CAD/CAM widgets. As a result, formalisms that rely on a fixed attribute, such as a rigid well-modeled shape or a constant color, are too narrow. Although systems that recognize objects based on rigid objects or color are potentially useful components of an object recognition system, they are not the full answer.

Instead, we propose that visual search be posed as a discrete control problem. The idea is that an object recognition system has a library of image understanding procedures that can be invoked to extract information from an image. The state of the system is (a function of) the information is has inferred from an image. Invoking a visual procedure is a discrete action that changes the (knowledge) state of the system. A goal state is one that includes the position of the target object instance. The high-level recognition problem is to find a control policy that minimizes the cost of reaching a goal state by selecting the appropriate action for each knowledge state.

We emphasize that such systems should be described in terms of control policies, rather than simple linear plans or strategies. Any time an image understanding algorithm is applied to an image, the result is unpredictable. A system that plans a linear sequence of actions and does not respond to the results of its actions is analogous to a feed-forward controller, and is as brittle. Control policies select the next action based in part of the results of previous actions, i.e. the knowledge state of the system, and are therefore more robust. (Note, however, that it is not necessary for the policy to be defined over every possible internal state, only those that can be reached from the start state using the control policy)

We should also make clear that we are proposing to borrow the formalism of discrete control systems, not necessarily the techniques. Researchers are still free to construct their state spaces and control policies however they wish, and to implement their system in the most efficient manner for their policy. The discrete control framework is a mathematical formalism for describing (and possibly replicating) systems, not a stricture to limit approaches.

Towards Reactive Non-Holonomic Path Planning for a Mobile Robot

Wendelin Feiten

The goal of this planner is to support an autonomous mobile robot in manoeuvring from one intermediate point of a wide range plan to the next one, in an a priori unknown environment. This planner is invoked in the situation that the robot cannot navigate through a narrow passage based on reactive behaviour alone, due to the nonholonomic constraints of the robot. Upon invokation, a process of incrementally mapping the environment in a planner grid map is started. It is initialised with the information from the obstacle avoidance grid map. This planner grid map is chosen to safely cover both intermediate points, the first one serving as start point and the second one as target point. The path planner plans a kinematically feasible free path based on the current state of the planner grid map. The generated plan consists of a sequence of desired steer angles valid for a fixed length path segment, as well as of a list of intermediate configurations. The planner is in the spirit of Barraquand's and Latombe's work on nonholonomic motion planning, including the distributed representation of the obstacles. This is natural in the situation of an a priori unknown environment and sensor data fusion on a grid map.

Task-Directed Sensor Planning

Gerhard Grunwald

Task-directed sensor planning adresses the problem of determining sensors and sensor data processing algorithms that are useful for executing a robot task. Because there are many different robot tasks, a formal correlation between the these robot tasks and its supporting sensors has to be established. In order to have both a flexible and a formal interface we define a sensor-requirement language. This permits that various clients like an operator in a teleoperation environment, a robot task planner, and implicitly formulated robot programs may require sensor support. Each sensor-requirement induces a set of plan-models represented as a directed graph of Logical Sensors. The plan-models are generated in an off-line process and are used as ingredients for the final sensor plan. The executable sensor plan is generated by the following three steps: 1.Analysis, 2. Potential plan generation, and 3. Instantiation and evaluation of the potential sensor plan.

Bio-Based Control for Autonomous Systems

Tom Henderson, Alyosha Efros

Our goal is to build robust, efficient, inexpensive autonomous robots that perform sensorimotor actions. Current computational approaches based on Turing Machines (TM) are fundamentally not robust (a one bit change in the TM specification produces a radically different machine). Moreover, digital schemes cannot compute over the Reals.

We propose to apply Prigogine's theory of irreversible processes in far from equilibrium systems to design robot systems which when immersed in a flow of sensory data create dissipative information structures to handle the data coherently. We are investigating Hoppenstaedt's VCON model of the neuron as a specific framework for cell assemblies. Some advantages of this approach include the use of the same model across multiple scales, motor control is directly incorporated, the explanatory power of the theory applies to both biological and non-biological systems, and finally, hardware implementation is straightforward. We are applying this to the development of low-level vision and mobile vehicle subsystems; e.g., saccades, focus, object tracking, etc.

How to Plan Under Uncertainty and Use a Logical Action Model, Too?

Joachim Hertzberg

A number of logical calculi for reasoning about action effects are readily available and well understood. Such calculi are needed as a basis for part of the internal reasoning that is necessary in generating action plans. For plan execution monitoring, these calculi may offer the advantage of deducing expected action effects; of these, the ones that are important for executing the rest of the plan can be passed on to the domain-appropriate sensor apparatus for mere checking, rather than freshly analyzing the scene resulting from action execution.

The talk informally presents PW as an example calculus. PW is robust towards certain aspects of imprecision and ambiguity in the domain description. Consequently, PW plans—or policies, as one might say—that reflect the calculus's results are robust with respect to the same forms of uncertainty. The talk sketches how to generate PW plans, the idea being anytime planning by approximating PW's results, rather than calculating them correctly. Finally, the talk summarizes the execution model underlying a reactive system guided by PW plans.

The talk is based on joint work with Gerd Brewka and with Sylvie Thiebaux (with contributions by Moti Schneider and Bill Shoaff).

Localisation, Environmental Modelling and Path Planning for Autonomous Mobile Robot Navigation

Ray Jarvis

For robust autonomous mobile robot navigation, particularly in initially unknown or time-varying environments, the subsystem functions of localisation, environmental modelling and path planning must be strongly coupled in a well balanced way.

Many localisation methodologies from odometry through to beacon based systems and, ultimately, natural land mark based strategies have been developed and applied with varying degrees of success in relatively limited application domains.

Also, a plethora of range finding devices based on operational principles from laser time-of-flight, ultrasonics, passive stereopsis, focus blur, and contrived lighting schemes have supported environmental modelling with varying degrees of success, again within limited application domains. The reliability, speed ,accuracy, robustness, cost, safety and scope of applicability of these methods are key factors governing their acceptability for robot navigation support in realistically complex environments.

Path planning depends critically on the quality of localisation and environmental modelling, especially so in the natural landmark navigation mode. This task can be pursued as a computational geometry problem and many practical methods have been inspired through theoretical considerations driven by academic curiosity. Certain approaches are limited in application through severe complexity growth, unrelistic assumptions or difficulty of extensions into higher dimensional spaces or modes requiring the accomodation of considerable uncertainty. Those path planning methods best able to extend from point to point optimal trajectory search to accomodate exploration, visit-all free space, multiple agent cooperation and time-varying environments are much in demand for mobile robot navigation support in realistic situations.

The Distance Transform approach (initially developed by the author in 1983) is a strong candidate in this regard. In particular, the rectangular tessellated space version of this approach easily handles all the modes of path planning listed above and ,in addition, lends itself to natural landmark based navigation schemes which can also be framed in a compatible space tessellation structure. In this way localisation, environmental modelling and path planning can be integrated through the same spatial representation format over which the Distance Transform approach operates at a number of different levels simultaneously.

This paper describes, in tutorial style, the type of interactions mentioned above and, in particular, promotes the Distance Transform methodology as an effective integrative force for autonomous mobile robot navigation ,especially in the natural landmark mode of operation, perhaps within a time-varying environment.

Symmetry Detection Algorithms and Applications in Object Recognition

Xiaoyi Jiang, Horst Bunke

In earlier papers we have proposed a new algorithm for symmetry detection of polyhedra and compared with other existing methods for polyhedral symmetry detection. In this talk, potential applications of symmetry detection in 3D object recognition are discussed. We consider a number of popular 3D object recognition paradigms, including interpretation tree search, hypothesize-and-test, invariant feature indexing of interpretation tables, pose clustering, and evidence based techniques. It is shown that symmetries can be used to avoid the generation of equivalent recognition results, or to identify and filter out the equivalent recognition results after they have been generated. The usefulness of symmetry information in object recognition and the availability of simple and efficient symmetry detection algorithms lead to our belief that symmetries should be exploited in any CAD-based object recognition system and a symmetry detection and encoding algorithm should be an integral part of the vision model preprocessor of such a system.

Collision Detection: A Geometric Approach

Pablo Jimenez, Carme Torras

Collision detection between geometric models is a useful tool for local path planning once a model of the environment has been built. Different collision detection methods (multiple interference detection, swept volume intersection, interference of extruded volumes in 4D, trajectory parameterization) rely on a static interference detection scheme.

We describe a collision detection method along a parameterized trajectory where static interference is solved using an edge-face intersection test, that allows the faces to be non-convex. Therefore, the described method is suitable for every non-convex polyhedra context, without the need of decomposing the non-convex polyhedra into convex entities. The computational effort can be reduced using a geometrical pruning technique, that exploits the concept of applicability relations, and which is based on a representation that we call Spherical Face Orientation Graph. The power of this pruning technique becomes evident in the case of translating convex polyhedra, where linear complexity is attained.

Competetive Strategies for Autonomous Systems

Rolf Klein

A strategy for a problem class P is called competitive with factor C if it allows each instance of P to be solved (with incomplete information) at a cost not exceeding C times the cost of an optimal solution (given full information). An example is the "doubling" strategy for finding a door in a long wall; from the starting position both the left and the right part of the wall are explored in turns, each time doubling the distance to the starting point. This gives a competitive factor of 9, which is known to be optimal. In order to find a goal in an unknown polygonal environment consisting of n edges, one can employ the same technique for exploring the shortest path tree from the start position to all vertices. This results in an O(n) competitve factor. In general, no constant factor can be achieved. But for the subclass of polygons where the two boundary chains leading from the start to the goal (both situated at vertices) are mutually weekly visible (="streets") a strategy is presented that guarantees a factor of 4.44 (even 1.8 in practice). Finally, we study the problem of finding the closest kernel point in a star-shaped polygon. If there is only a single reflex vertex obstructing the view then an optimal strategy with factor 1.212 exists. We present a strategy for the general case with a conjectured factor of 4.141. Its analysis depends on an upper bound for the arc length of curves that "move away from their past" in one direction. These result are based on joint work with Ch. Icking and L. Ma.

A Distributed Control Architecture for Autonomous Robot Systems

Thomas Längle, Tim C. Lüth, Ulrich Rembold

The main advantage of distributed controlled robots and subsystems is the decentralized task execution by the system components. This way, properties for the design of flexible intelligent control architectures like modularity, fault-tolerance, integrability and extendibility are easy to obtain, further it is possible to use the concepts of distributed knowledge and decentralized world representation. On the other hand, coordination between the components, for example path planning for collision avoidance between both manipulators in a two-arm-system, is very difficult to guarantee. To explain these concepts, the Karlsruhe Autonomous Mobile Robot KAMRO is considered which is being developed at IPR. The robot system consists of several subcomponents like two manipulators, hand-eye- cameras, one overhead camera and a mobile platform. Extensions to the distributed control architecture KAMARA (KAMROs Multi Agent Robot Architecture) are described that are responsible to overcome coordination problems, for example caused by the independent task execution of both manipulator systems. Further, it is explained which way the decentralized world representation can be used for parallel task execution.

Fractal Coding of Image Sequences for Motion Planning

Paul Levi, Niels Mache, Thomas Harrer

Fractal encoding of images delivers high compression rates and good acurracy. With our fractal encoding method image sequences can be encoded and decoded at high speed and can be used to enhance following image processing. The encoding of an complex image sequence with 384x288 pixel size runs with approximately 0.61 frames/s (decoding with X-Window display and 8-bit dithering: 17 frames/s) on a Sparc Station 10 and obtains compression rates between 30:1 and 70:1. The delay between encoding and decoding of image sequences is less then 1 frame. This means that encoding and decoding of image sequences can be done with very minimal delay. Our fractal method doesn't use any statistical data encoding, so it can be easily parallelized. This fractal encoding method is very promising for precise reconstruction of distance images from stereo image sequences.

Rasterized Motion Planning

Heinrich Müller

The following classical motion planning problem is addressed: Given is a set of polygonal obstacles in d-dimensional space. For tw arbitrary query points it has to be decided whether there is a collision-free path between them in the scene. If there is any, a path should be reported. A straightforward solution is to rasterize the space into a d-dimensional grid of cells and search for the path in the underlying graph. The problem with that however, is space requirements for higher dimensions d. Two overcome this difficulty retraction is used. The retraction network is constructed by calculating the minimum over the distance functions of the obstacles. A rasterized solution for $d = 2$ is obtained by z-buffering the polygon, an approach of computer graphics for visibility calculation for which powerful hardware is available today. For $d > 2$, the distance functions are restricted to 2d slices so that z-buffering also can be applied in that case. From the resulting d-dimensional rasterized space the edges of retraction are extracted by a generalization of the marching cubes approach. The overall advantage of the presented solution is a working space independent of the dimension which makes this approach practicable from that point of view. A limit on practical dimensions d still exists with respect to processing time, which however is one order better than with other approaches thus extending the treatable dimensions somewhat. Examples of an implementation for $d = 2$ and $d = 3$ are presented.

Representation and Planning for Behaviour-Based Robots

Jean-Pierre Müller, Miguel Rodriguez

When dealing with autonomous robots, the definition of autonomy is important. In particular, any description in terms of functions from input to output however complicated the functions can be, would still be heteronomous. Autonomy implies internally an organization of self-contained and self-referential processes. In this context, the idea of combining reactive behaviours with goal-oriented mechanisms and of using representations to do the latter remains valid but has to be reformulated. First, we distinguish the internal sensory-motor processes from the behaviours produced when they are interacting with an environment. Second, a representation cannot be a representation of an external world, inaccessible to the robot anyway, but only of the interaction history as perceived by the robot through its behaviours. In this contribution, we propose such a representation as a graph encoding of the interaction history and show its uses for learning, localizing and planning without having to refer to any external environment.

Sensor Fusion and Learning for Environmental Modelling

Robin R. Murphy

We are interested in developing an architecture for autonomous mobile robots which is capable of robustly interpreting observations from multiple sensors. Our approach relies on the categorization of sensor configurations into one of three possible fusion states which define acceptable action to compensate for noise and drift (e.g., fault tolerance). Learning for sensor fusion is important as robots operating in unknown and partially known environments must be capable of learning the fusion state associated with the sensors as well as the relevant environmental models. Preliminary results from data taken with color video, b&w video, and ultrasonics indicate that the relative utility of each sensor for a specific task and environment can be learned. Other work with automatic target recognition suggests that fuzzy theory revision can be used to learn and update object and scene models.

Motion Interpolation and Approximation Based on CAGD Methods

Helmut Pottmann, Michael Wagner

We introduce piecewise rational motions, expressed in B–spline form. Rational B–spline motions possess a linear control structure consisting of affine control positions; these are formed by the de Boor points of the trajectories which are rational B–spline curves. The linear control structure allows us to apply the variety of B–spline algorithms to motion design problems. In particular, it provides a hierarchical set of enclosing polyhedra to the volume swept out by a moving polyhedron. This simplifies collision detection. Besides the affine control figure there is another non–linear control structure, expressible in terms of Euclidean kinematics. This structure can serve for interactive motion design.

Rational B–spline motions are then used to solve the problem of interpolating a given set of positions with a C^2 motion. This problem arises for example in path–planning for industrial robots and in computer animation. Whereas in 3–space the resulting motions are necessarily of degree 6, one can solve the problem in the plane with piecewise quartic motions. Further interpolation techniques and algorithms for approximating a set of positions with rational B–spline motions have been developed by B. Jüttler (Darmstadt).

A main advantage of the proposed technique over previous solutions by Shoemake, Ge, Ravani and others is that it is built directly onto standard CAD algorithms and inherits their advantages.

Robot Navigation: A Simple Guidance System for a Complex Changing World

Erwin Prassler

An approach to motion planning amongst arbitrarily moving unknown objects is presented. As opposed to other approaches to motion planning we avoid the assumption that the motion parameters and the shape of moving objects are known *a priori* or can be predicted over longer time intervals. By giving up this assumption, traditional methods such as space-time representation and search in space-time no longer apply. Our approach is based on a massively parallel network of simple processing elements. A relaxation process, which is driven by the simultaneous execution of a simple formula in these processing elements, creates a two-dimensional distribution of real numbers, denoted as potentials, which encodes information about collision-free trajectories. Our approach is different from classical algorithmic motion planning in that we do not employ an analytical planning or search algorithm. Instead, desired behaviors, such as the avoidance of moving objects, are achieved by adroit manipulation of the two-dimensional potential distribution and by a gradient descent through the emerging distribution.

Line Based Modelling from Laser Radar Data

Ewald von Puttkamer

For autonomous mobile robots intended to operate in an indoor environment in bureau like rooms the environment may be modelled by lines, desribing walls and doors among other objects. To recognize these structures a laser radar may be used. Taking radar shots from a moving robot, corrections have to be considered and the angular momentum of the laser head stabilized. There are various methods to deduce lines from radar plots. Lines from different plots may be fused if the inevitable drift effects in internal odometry can be compensated. Radar plots showing straight structures may be used to give orientation as well as position with respect to the staight structures in the environment thus being landmarks for drift correction. From a line based despription of the environment walls and doors can be recognized. Elongating lines marked as walls, the edges of a polygon, decribing a room and the throughways into other rooms can be deduced. Being in a certain room describes in a generalized way the momentary "situation" the robot is in. Rooms form the nodes of a topologic graph, the vertices the throghways to other rooms. Inside a room the robot can orient itself and rerecognize the room from characteristics of its interior and its coarse position.

Projective Reconstruction from Uncalibrated Images

Long Quan

There are three projective invariants of a set of six points in general position in space. It is well known that these invariants cannot be recovered from one image, however an invariant relationship does exist between space invariants and image invariants. This invariant relationship will first be derived for a single image. Then this invariant relationship is used to derive the space invariants, when multiple images are available.

This paper establishes that the minimum number of images for computing these invariants is three, and invariants from three images can have as many as three solutions. Algorithms are presented for computing these invariants in closed form.

The accuracy and stability with respect to image noise, selection of the triplets of images and distance between viewing positions are studied both through real and simulated images.

Application of these invariants for projective reconstruction is also presented, this extends the results of Faugeras (1992) and Hartley *et al.* (1992) for two uncalibrated images to the case of three uncalibrated images.

Fusion Rule Estimation in Multiple Sensor Systems Using Learning

Nageswara S.V. Rao

A formal framework for estimating fusion rules for a system of N sensors, based on a set of examples, is presented. No knowledge about the probability distributions of sensor errors is assumed. Given an input vector $x \in \Re^d$, the sensor S_i, $i = 1, 2, \ldots, N$, generates output $y_i \in \Re^d$ according to an unknown density $p_i(y_i|x)$. For a fusion rule $f : \Re^{Nd} \mapsto R$, chosen from a family Λ, the expected error is defined as

$$I(f) = \int [x - f(y_1, y_2, \ldots, y_N)]^2 p_Y(y_1, y_2, \ldots y_N|x) p_X(x) dy_1 dy_2 \ldots dy_N dx$$

where $p_Y(.)$ depends on $p_i(.)$'s, and $p_X(.)$ is the distribution of the input. Given a sample $(x^{(1)}, y^{(1)}), (x^{(2)}, y^{(2)}), \ldots (x^{(l)}, y^{(l)})$, where $y^{(j)} = (y_1^{(j)}, y_2^{(j)}, \ldots, y_N^{(j)})$ corresponds to the input $x^{(j)}$, we consider the conditions under which an estimator $\hat{f} \in \Lambda$ can be computed such that

$$P[I(\hat{f}) - I(f^*) > \epsilon] < \delta$$

for sufficiently large l. We present three algorithmic methods and the corresponding technical conditions under which the above criterion can be ensured. The techniques are based on (i) stochastic approximation, (ii) empirical estimation and potential functions, and (iii) regression estimation. Two experimental scenarios involving (a) identification of glassware in a structured environment, and (b) recognition of a narrow doorway by a mobile robot equipped with an array of ultrasonic and infrared sensors, are described to illustrate the applicability of the proposed methods.

Robotic Radiosurgery

Achim Schweikard

We describe a radiosurgical system based on a novel medical linear accelerator of particularly light weight, a six degree-of-freedom robotic arm and an online x-ray vision system. The system introduces a class of radiosurgical procedures, termed *non-stereotactic*, or *image-guided* radiosurgery. A treatment planning subsystem based on new paradigms for inverse planning was developed in an interdisciplinary project at Stanford University in conjunction with Accuray Inc., Santa Clara. Two patients have been treated with a fully integrated system prototype at Stanford University Medical Center. The new system has the potential for revolutionary changes in radiosurgery by allowing for high accuracy targeting, fractionated treatment and highly conformal radiosurgical treatment of non-spherical lesions. Furthermore, it is expected that image-guided procedures will replace radiotherapeutical methods for many extra-cranial lesions.

Planning with Uncertainty of Vision

Yoshiaki Shirai

Planning for a mobile robot often depends on the environment which is obtained by robot vision. In such cases, the cost and uncertainty of vision should be taken into consideration as well as the cost of motion. The problem can classified according the nature of the uncertainty and the dimension of the search space. Three cases are shown and the difficulty of the problem is described.

The first case is planning of motion along given paths to reach a goal. First, a robot is guided along a corridor by a human to make a map of the corridor in terms of landmarks such as doors, stairs, or branches. Next, for a given goal position, the robot makes a plan to reach the destination in the shortest time by combining dead reckoning, searching a part of a landmark, and verifying the landmark. Considering uncertainty of the map, dead reckoning, and vision, the problem is reduced to a graph search.

The second case is to make a motion and sensing plan in two dimensional space in order to reach a given destination. The vision uncertainty is the quantization error of a stereo vision. The error distributions are formulated for fusion of the current distribution and the expected distribution. The plan minimizes the total cost which consists of the cost of motion and that of vision. This is formulated with a recursive formula which should be solved numerically by quantizing the two-dimensional space. It requires a large amount of computation to solve this simple problem.

In the third case, the vision uncertainty include both the quantization error and the matching error of the stereo vision. The ambiguity of matching can be resolved by observing the candidate position from a different direction. In this case, similar recursive formula is obtained. It also requires much computation. Currently, A* algorithm is used to reduce the search. However, heuristic knowledge will be useful to further constrain the search.

Function-Based Object Recognition

Louise Stark, Kevin Bowyer

A function-based recognition system reasons about observed object shape in order to determine what function the object might serve and then classifies the object accordingly. Thus the recognition performed by a function-based system is inherently more generic than that performed by a system which matches an observed object against a predefined set of geometric models.

Our research project deals with exploring the use of knowledge about object functionality as a means toward generic object recognition. A succession of increasingly more sophisticated versions of the GRUFF (Generic Recognition Using Form and Function) system has been implemented and evaluated. The results demonstrate the basic feasibility of our approach.

An overview of the GRUFF approach as it applies to function-based analysis of static 3-D shape is presented. This pure shape-based analysis was performed on over 400 test object shapes. Having shown the feasibility of the approach, further extensions to the system have been made. Three recent extensions are also presented. The first involves an analysis of incomplete descriptions of object shape of the type that is acquired from real sensor data. A second extension of our work deals with planning and executing a sequence of interactions with an object to confirm functionality. A third extension explores the derivation of an articulated shape model from an observed sequence of 3-D shape and then reasoning about its possible functionality.

Exact Motion Planning amidst Fat Obstacles (and in Environments of Low Obstacle Density)

A. Frank van der Stappen

The efficiency of algorithms for the exact solution of the motion planning problem depends, to a large extent, on the complexity of the free space. Unfortunately, the theoretical free space complexity can be very high. In many practical cases, however, the actual complexity will remain far below the theoretical worst-case bounds. It turns out that the complexity is only linear in the number of obstacles if the density of the obstacles (relative to the size of the robot) is small. Such a low obstacle density follows for example if the obstacles are 'fat' and the robot is not too large compared to the obstacles. These realistic circumstances lead to remarkable efficiency gains for a number of existing planar motion planning algorithms. More importantly, the assumptions induce a specific structure of the free space that allows to reduce the problem of decomposing the free space to the problem of partitioning some lower-dimensional subspace of the configuration space. The approach results in efficient algorithms for various instances of the motion planning problem.

Spatial Indices and Motion Planning

Knut Verbarg

We are interested in the application of spatial indices in motion planning.

A SPATIAL INDEX is a data structure to manage and represent a large set of simple spatial objects to support fast access through spatial attributes. We present two spatial indices, both developed in Würzburg.

The MONOTONOUS BISECTOR TREE (MBT) is due to C. Zirkelbach. It is a binary rooted tree, which hierarchically partitions the scene with bisectors. For convex polyhedrons in N-dimensional real space and any L_p-metric ($1 \leq p \leq$ infinity), we are able to construct the MBT in time $O(n\ logn)$, with linear space and logarithmic height, where n denotes the complexity of the scene.

The C-TREE is an enhancement of the MBT. It adds the paging-concept, which allows to manage huge scenes in practice. Like the MBT it can be constructed in time $O(n\ logn)$. Dynamic insertion of objects is performed in $O(log^2 n)$ amortized worst-case time. Objects can be deleted in amortized $O(n)$ or in amortized $O(log^2 n)$, if the actualization of cluster radii can be delayed. In all cases logarithmic height and linear space requirements are preserved.

We report on extensive experimental results, which show both data structures to be robust and efficient. Moreover the paging-concept is necessary and successful to handle huge data sets that can not be stored in main memory.

Finally, we mention some approaches to use spatial indices in robotics.

Dagstuhl-Seminar 9443

List of Participants

Frank **Ade**
ETH Zürich
Inst. für Kommunikationstechnik
Fachgruppe Bildwissenschaft
Gloriastr. 35
CH-8092 Zürich
Switzerland
ade@vision.ethz.ch
tel.: +41 1 632 52 80

Suguru **Arimoto**
Faculty of Engineering
Dept. of Math. Eng. &
Information Physics
7-3-1 Hongo
Bunkyo-ku
Tokyo 113
Japan
arimoto@arimotolab.t.u-tokyo.ac.jp
tel.: +81-3-3812-2111 Ext. 69 30

Robert C. **Bolles**
SRI International
Artificial Intelligence Center
333 Ravenswood Ave.
Menlo Park CA 94025
USA
bolles@ai.sri.com

Horst **Bunke**
Universität Bern
Inst. für Informatik und
Angewandte Mathematik
Länggassstr. 51
CH-3012 Bern
Switzerland
bunke@iam.unibe.ch
tel.: +41 31 6314451

Claude **Caillas**
ETCA/CREA/SP
Etablissement Technique Central
de l'Armement
16bis Ave. Prieur de la Cote d'Or
F-94114 Arcueil
France
ccaillas@etca.Fr
tel.: +33-1-42.31.92.32

Henrik I. **Christensen**
Aalborg University
Laboratory of Image Analysis
Institute of Electronic Systems
Fr. Bajers Vej 7
DK-9220 Aalborg East
Denmark
hic@vision.auc.dk
tel.: +45 98 15 11 33

Rüdiger **Dillmann**
Universität Karlsruhe
Inst. für Prozeßtechnik & Robotik
Kaiserstr. 12
D-76128 Karlsruhe
Germany
dillmann@ira.uka.de
tel.: +49-721-608-38 46

Bruce **Draper**
University of Massachusets
Dept. of Computer Science
Lederle Graduate Research Center
Amherst MA 01003
USA
bdraper@cs.unuss.edu
tel.: +1-413-545-13 20

Wendelin **Feiten**
SIEMENS AG - ZFE ST SN 45
Zentrale Forschung und Entwicklung
Otto-Hahn-Ring 6
D-81739 München
Germany
wendelin.Feiten@zfe.sienmens.de
tel.: + 4989 636 3379

Gerhard **Grunwald**
DLR-Oberpfaffenhofen
Institut fur Robotik und Systemdynamik
Münchener Str. 20
D-82234 Wessling
Germany
grunwald@donau.df.op.dlr.de
tel.: +49-8153-28-24 06

Thomas C. **Henderson**
University of Utah
Computer Science Department
Salt Lake City UT 84112
USA
tch@cs.utah.edu
tel.: +1-801-581-36 01

Joachim **Hertzberg**
GMD
53731 St. Augustin
Germany
hertzberg@gmd.de
tel.: +49-2241/14-2674

Ray **Jarvis**
Monash University
Dept. of Electrical and Computer System
Wellington RD
Clayton Victoria 3168
Australia
ray.jarvis@eng.monash.edu.au
tel.: + 61 3 905 3470

Xiaoyi -Y. **Jiang**
Universität Bern
Inst. für Informatik und
Angewandte Mathematik
Länggassstr. 51
CH-3012 Bern
Switzerland
jiang@iam.unibe.ch
tel.: +41-31-631-86 99

Takoe **Kanade**
Carnegie Mellon University
The Robotics Institute
Schenley Park
Pittsburgh PA 15213
USA
kanade@ius3.cs.cmu.edu
tel.: +1-412-268-3016

Rolf **Klein**
FernUniversität Hagen
Praktische Informatik VI
Elberfelder Straße 95
D-58084 Hagen
Germany
rolf.klein@fernuni-hagen.de
tel.: +49-2331-987 327

Thomas **Längle**
Universität Karlsruhe
Fakultät für Informatik IPR
Geb. 40.28
Postfach 6980
D-76049 Karlsruhe
Germany
laengle@ira.uka.de
tel.: +49-721-608-40 49

Paul **Levi**
Universität Stuttgart
IPVR (Institute for Parallel and Distribute
High Performance Computing)
Breitwiesenstr. 20-22
D-70565 Stuttgart
Germany
paul.levi@informatik.uni-stuttgart.de
tel.: +49-711 7816-387

Jean Pierre **MÜller**
Universite de Neuchâtel
Institut d'Informatique
et Intelligence Artificielle
rue Emile Argand 11
CH-2007 Neuchâtel
Switzerland
jean-pierre.muller@info.unine.ch
tel.: +41-0-38-23 27 07

Heinrich **Müller**
Universität Dortmund
FB Informatik Lehrstuhl VII
D-44221 Dortmund
Germany
mueller@ls7.informatik.uni-dortmund.de
tel.: +49-231-755-63 24

Niels **Mache**
Universität Stuttgart
IPVR
Breitwiesenstr. 20-22
D-70565 Stuttgart
Germany
niels.mache@informatik.uni-stuttgart.de
tel.: +49-711 7816-2 45

Robin **Murphy**
Colorado School of Mines
Dept. of Mathematical and Comp. Sci.
Golden CO 80401-1887
USA
rmurphy@mines.colorado.edu
tel.: +1-303-273-3874

Helmut **Noltemeier**
Universität Würzburg
Informatik I
Am Hubland
D-94074 Würzburg
Germany
noltemei@informatik.uni-wuerzburg.de
tel.: +49-931 888-5054 / 0931 888-5055

Helmut **Pottmann**
Technische Universität Wien
Institut für Geometrie
Wiedner Hauptstraße 8--10/113
A-1040 Wien
Austria
pottmann@egmvs2.una.ac.at
tel.: +43-1-58801-53 50

Erwin **Prassler**
FAW Ulm
Helmholtzstr. 16
D-89081 Ulm
Germany
prassler@faw.uni-ulm.de
tel.: +49-731-501-621

Ewald **von Puttkamer**
Universität Kaiserslautern
FB Informatik
Erwin-Schrödinger-Str.
D-67653 Kaiserslautern
Germany
puttkam@informatik.uni-kl.de
tel.: +49-631-205-22 76

Long **Quan**
LIFIA
46 Avenu Felix Viallet
38031 Grenoble
France
Long.Quan@imag.fr
tel.: +33-7657-46-66

Nageswara **Rao**
Oak Ridge National Laboratory
Center for Eng. Syst. Adv. Res.
P.O. Box 2008
Oak Ridge TN 37831-6364
USA
nrao@dizzy.epm.ornl.gov
tel.: +1-(615) 574-7517

Achim **Schweikard**
TU München
Institut für Informatik
Orlanstr. 34
D-81667 München
Germany
(as@cs.stanford.edu)

Yoshiaki **Shirai**
Osaka University
Faculty of Engineering
Yamada-oka 2-1
Osaka 565
Japan
shirai@cv.ccm.eng.osaka-u.ac.jp
tel.: +81- 6-879- 7331

Frank **van der Stappen**
University of Utrecht
Dept. of Mathematics
P. O. Box 80.010
NL-3508 TA Utrecht
The Netherlands
stappen@math.ruu.nl
tel.: +31-30-53 15 29

Louise **Stark**
University of the Pacific - Stockton
School of Engineering
Baun Hall
3601 Pacific Avenue
Stockton CA 95211
USA
stark@napa.eng.uop.edu
tel.: +1-209-946-30 71

Carme **Torras**
Universidad Politécnica de Cataluña
Instituto de Cibemetica
Diagonal 647 / 2a Planta
E-08028 Barcelona
Spain
torras@ic.upc.es
tel.: +34-3-401-66 61

Knut **Verbarg**
Universität Würzburg
Informatik I
Am Hubland
D-97074 Würzburg
Germany
verbarg@informatik.uni.wuerzburg.de
tel.: +49-931-888-50 58

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