06421 Abstracts Collection
Robot Navigation
— Dagstuhl Seminar —

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Abstract. From 15.10.06 to 20.10.06, the Dagstuhl Seminar 06421 "Robot Navigation" was held in the International Conference and Research Center (IBFI), Schloss Dagstuhl. During the seminar, several participants presented their current research, and ongoing work and open problems were discussed. Abstracts of the presentations given during the seminar as well as abstracts of seminar results and ideas are put together in this paper. The first section describes the seminar topics and goals in general. Links to extended abstracts or full papers are provided, if available.

Keywords. Motion planning, robotics, computational geometry, online algorithms

06421 Executive Summary – Robot Navigation

For quite a number of years, researchers from various fields have studied problems motivated by Robot Navigation. On the theoretical side, a robot is faced with a number of algorithmic issues that are geometric in nature. This includes mapping a given environment, searching all possible locations in such an environment, or localizing the robot's position on a given map; typically, available information is visibility-based, but motion-planning may also require the computation of a collision-free trajectory for a rigid body, if one exists. These geometric aspects are pursued in the field of **Computational Geometry**, where quite a bit of expertise has been developed, including deep results on visibility problems and motion planning.

Another crucial feature of robot navigation is that path-planning has to be performed without full knowledge of all necessary data; such information only becomes available during the course of the robot's motion, requiring optimization with incomplete information. Complete knowledge of the scenario only becomes

known after a strategy has actually been applied. This means that in addition to the geometric issues described above, an algorithm has to protect against various possibilities (including faulty sensors or inaccurate data), instead of basing its decisions on a complete description of the tasks ahead. Problems of this type are studied in the field of **Online Algorithms**.

On the other hand, computer scientists and engineers from the field of **Robotics** who work with real robots have made tremendous progress in developing systems that can perform a multitude of practical tasks. These technical possibilities give rise to a number of scenarios that have been studied in theory for a number of years. Thus, practitioners can benefit from the expertise of theoreticians. On the other hand, actual real-world scenarios tend to impose requirements that are more or less different from the ones previously considered in theory; moreover, some novel capabilities give rise to additional theoretical questions that pose new and exciting challenges.

A predecessor workshop took place December 7 to 12, 2003. An excellent example of a successful interaction between theoreticians and practitioners is the direct result of this workshop: The video "Searching with an autonomous robot" (available at the website http://videos.compgeom.org/socg04video/) is based on discussions between the theoreticians Sándor Fekete (TU Braunschweig) and Rolf Klein (Universität Bonn), and the practitioner Andreas Nüchter (Fraunhofer Institute for Autonomous Intelligent Systems), who met at this Dagstuhl workshop. Using the specifications of an existing autonomous robot, a new strategy was developed for optimally locating an object hidden behind a corner. Currently, further work on broad extensions of this scenario is in the planning, showing that theory meeting practive can lead to real breakthroughs. This fruitful contact has only become possible by the previous Dagstuhl workshop on Robot Navigation.

The workshop in 2006 brought together 31 researchers from 9 different countries. The 25 presentations, varying in length, covered a large variety of topics, including selected results from online algorithms, search problems and search games, self-localization, motion and path planning, mapping, and swarm navigation. Talks were spread over the week to allow for plenty of time for discussions between the talks, thus giving participants a chance to exchange problems and ideas. We are positive that many of them will lead to new results and publications.

The growing demand and opportunities for close interaction between practitioners and theoreticians became apparent at the Open Problem Session, which saw a very lively debate on how interaction between theory and practice is seen by the various communities and how it might be improved. The central question seemed to be what is the best or correct way to model real robots such that theoretical results become meaningful for practitioners.

As usual, Schloß Dagstuhl proved to be an excellent place to hold a great meeting, so we would not only like to thank the participants of the seminar for making this a very successful event, but also the Dagstuhl staff for providing a friendly and stimulating working environment.

Keywords: Motion planning, robotics, computational geometry, online algorithms

Joint work of: Fekete, Sándor; Fleischer, Rudolf; Klein, Rolf; López-Ortiz, Alejandro

Extended Abstract: http://drops.dagstuhl.de/opus/volltexte/2007/872

Hide-and-Seek on a Network

Steve Alpern (London School of Economics, GB)

Given a finite network Q, on may consider the following hide and seek game $G = G(Q)$. The Hider (maximizer) simply picks a point H in G, not necessarily a node. The Searcher chooses a unit speed path $S(t)$ that covers Q. The payoff T is the time taken for the Searcher to find the Hider, $T = \min\{t : S(t) = H\}$. The network Q is said to be 'simply searchable' if a Chinese Postman path, traversed equiprobably in either direction, is optimal for the Searcher. It is called 'easily hidable' if the uniform distribution is an optimal strategy of the Hider. We show that symmetric networks are easily hidable. For such networks an optimal search strategy is a Utilitarian Postman path (minimizes the expected time to reach a random point), traversed equiprobably in either direction.

Keywords: Search, game, network, Chinese Postman path

Optimal Simulation of Anytime Algorithms using Contract Algorithms

Spyros Angelopoulos (University of Waterloo, CA)

A contract algorithm is an algorithm which is given, as an input parameter, a specified amount of allowable computation time. The algorithm must then compute a solution within the alloted time. An interruptible algorithm, in contrast, can be queried at any point during its execution and must be able to output a solution at the exact query point. It is known that interruptible algorithms can be simulated by contract algorithms using iterative deepening techniques; however, the simulation incurs a penalty in the performance of the solution, as measured by the so-called acceleration ratio.

In this talk I will present optimal upper and lower bounds for the acceleration ratio resulting from such simulation strategies. This resolves an open conjecture by Bernstein, Finkelstein and Zilberstein, who gave an optimal strategy under the restriction of round-robin and length-increasing contract schedules but whose optimality in the general, unrestricted case had remained open.

Joint work of: López-Ortiz, Alejandro; Angelopoulos, Spyros; Hamel, Angele

See also: A. López-Ortiz, S. Angelopoulos, A. Hamel. Optimal Scheduling of Contract Algorithms for Any-time Problems. Proceedings of the 21st National Conference of the American Association for Artificial Intelligence (AAAI), 2006.

Distance Trisector Curves in Regular Convex Distance Metrics

Tetsuo Asano (JAIST - Ishikawa, J)

Given a set of polygonal obstacles in the plane, it is rather easy to compute a shortest path between two specified points.

Unfortunately, such a shortest path is most dangerous for robots because it connects corner to corner. If we prefer a safe path, we could use a Voronoi diagram for obstacles and took a path along Voronoi edges.

In this talk we propose another Voronoi diagram based in trisector curves instead of perpendicular bisectors for ordinary Voronoi diagrams.

The Voronoi diagram has many mathematically interesting properties, but theoretically it is quite hard even to draw it. Then, we introduce a notion of convex distance metric by which we can draw Voronoi edges as polygonal chains.

Keywords: Trisector curve, distance metric, Voronoi diagram

Full Paper:
http://www.jaist.ac.jp/~t-asano/e-index.htm

Adaptive Analysis of On-line Algorithms

Reza Dorrigiv (University of Waterloo, CA)

On-line algorithms are usually analyzed using competitive analysis, in which the performance of on-line algorithm on a sequence is normalized by the performance of the optimal on-line algorithm on that sequence. In this paper we introduce adaptive/cooperative analysis as an alternative general framework for the analysis of on-line algorithms. This model gives promising results when applied to two well known on-line problems, paging and list update. The idea is to normalize the performance of an on-line algorithm by a measure other than the performance of the on-line optimal algorithm OPT. We show that in many instances the perform of OPT on a sequence is a coarse approximation of the difficulty or complexity of a given input. Using a finer, more natural measure we can separate paging and list update algorithms which were otherwise undistinguishable under the classical model. This creates a performance hierarchy of algorithms which better reflects the intuitive relative strengths between them. Lastly, we show that, surprisingly, certain randomized algorithms which are superior to MTF in the classical model are not so in the adaptive case. This confirms that the ability of the on-line adaptive algorithm to ignore pathological worst cases can lead to algorithms that are more efficient in practice.

Keywords: On-line algorithms, paging, adaptive/cooperative analysis

Joint work of: Dorrigiv, Reza; López-Ortiz, Alejandro

Searching with an Autonomous Robot

Sándor Fekete (TU Braunschweig, D)

We discuss online strategies for visibility-based searching for an object hidden behind a corner, using Kurt3D, a real autonomous mobile robot. This task is closely related to a number of well-studied problems.

Our robot uses a three-dimensional laser scanner in a stop, scan, plan, go fashion for building a virtual three-dimensional environment.

Besides planning trajectories and avoiding obstacles, Kurt3D is capable of identifying objects like a chair.

We derive a practically useful and asymptotically optimal strategy that guarantees a competitive ratio of 2, which differs remarkably from the well-studied scenario without the need of stopping for surveying the environment.

Our strategy is documented in a video. This work resulted from an interdisciplinary collaboration, originating at a previous Dagstuhl workshop.

Keywords: Searching, visibility problems, watchman problems, online searching, competitive strategies, autonomous mobile robots, three-dimensional laser scanning, Kurt3D

Joint work of: Fekete, Sándor; Klein, Rolf; Nüchter, Andreas

Full Paper:
http://arxiv.org/abs/cs.RO/0404036

See also: Computational Geometry: Theory and Applications, 34 (2), 2006, pp. 102-115

Network Search Games: some old and new results

Shmuel Gal (University of Haifa, IL)

This survey is concerned with searching a network looking for a hidden immobile object, or target.

The searcher chooses a continuous path in the network and finds the target as soon as he reaches its location. The situation is analyzed as a Search Game assuming that the 'target' is an independent player who wishes to hide. Thus, we use a worst case analysis looking for a search strategy that guarantees minimum expected time for any hiding strategy of the target. The search problems covered by this research are important for the usual applications (civil or military) of Search Theory and also for some other applications such as the surveillance of communication networks in order to deter eavesdroppers.

We will focus on characterizing networks which should be searched using a simple strategy. A network is called simply searchable if an optimal search strategy can be obtained as follows. Find a minimal path that visits all the arcs and traverse it with probability half in each direction (either forward or backward). In the case that the searcher has to start from a fixed point the minimal path has to start and to end at the starting point so that it need to be closed (a Chinese postman tour). For a fixed starting point, Gal (2000) showed that a network is simply searchable if and only if the graph is weakly Eulerian, (i.e., it consists of several Eulerian sub-graphs connected in a tree-like structure). In the more recent research we allow the searcher to choose the starting point of his search trajectory.

We show that trees are simply searchable. Then, we extend the result to a family of networks which also includes some unions of trees and Eulerian curves. We also present the recent result that, contrary to the fixed start case, simple searchability is not a topological property.

This talk presents a survey of the results but also describes the ideas used in the proofs of the theorems for both fixed start and arbitrary start problems.

Keywords: Search Games, Arbitrary Start, Chinese Postman, Weakly Eulerian

Joint work of: Gal, Shmuel; Alpern, Steve ; Baston, Vic ; Dagan, Arnon

Online distributed strategies for maintaining connectivity in mobile networks

Jaroslaw Kutylowski (Universität Paderborn, D)

For a robotic team engaged in work on a large terrain it is crucial to keep in contact using a wireless network. In many situations one cannot rely on any existing infrastructure, thus the usage of ad-hoc networks is the only possibility to establish a communication infrastructure.

Considering large terrain and/or harsh atmospheric conditions, wireless links may be limited to a transmission distance which does not yield a connected communication graph between employed robots. We propose a remedy to this problem by establishing a mobile backbone structure, composed of stations which act as repeaters for wireless links.

We study the problems occuring when using repeaters as a mobile backbone. We develop highly distributed and local strategies which allow the stations to maintain the backbone and ensure connectivity under various dynamics of the system. Our focus is both on efficiency of the strategies developed and on providing solutions which require only a local view of the system.

The talk gives a brief overview over problems, solution ideas and open questions.

Keywords: Ad-Hoc Networks, Distributed Algorithms, Self-Organization

Competitive Online Searching for a Ray in the Plane

Elmar Langetepe (Universität Bonn, D)

We consider the problem of a searcher that looks, for example, for a lost flashlight in a dusty environment. The searcher finds the flashlight as soon as it crosses the ray emanating from the flashlight. In order to pick it up, the searcher moves to the origin of the light beam. We compare the length of the path of the searcher to the shortest path to the goal.

First, we give a search strategy for a special case of the ray search—the window shopper problem—, where the ray we are looking for is perpendicular to a known ray. Our strategy achieves a competitive factor of $1.059\ldots$, which is optimal. Then, we consider rays in arbitrary position in the plane. We present an online strategy that achieves a factor of $22.513\ldots$, and give a lower bound of $2\pi\, e = 17.079\ldots$.

Keywords: Online motion planning, competitive analysis, ray search

Joint work of: Eubeler, Andrea; Fleischer, Rudolf; Kamphans, Tom; Klein, Rolf; Langetepe, Elmar; Trippen, Gerhard

Full Paper: http://drops.dagstuhl.de/opus/volltexte/2007/868

An Extremely Fast, Exact Algorithm for Finding Shortest Paths in Static Networks with Geographical Background

Ulrich Lauther (Siemens - München, D)

We present a new algorithm for fast and exact calculation of shortest paths in graphs with geometrical information in nodes (coordinates), e.g.road networks. The method is based on preprocessing and is therefore best suited for static graphs, i.e. graphs with fixed topology and edge costs. In the preprocessing phase, the network is divided into regions and edge flags are calculated that indicate whether an edge belongs to a shortest path into a given region. In the path calculation step, only those edges need to be investigated that carry the appropriate flag. As compared to a classical Dijkstra implementation, we achieve a typical speed-up by a factor of 150 ... 500 on US-roadmaps provides by the 9th DIMACS challenge, containing between 260.000 and 6.3 million nodes.

The concept of edge flags and how to use them in the path finding algorithm is discussed in this talk; the preprocessing step is just outlined.

Keywords: Shortest path, preprocessing

Alternative Models for Online Analysis

Alejandro López-Ortiz (University of Waterloo, CA)

The worst case nature of the competitive ratio can lead to algorithms that focus on the worst case at the expense of the every-day case as well as to lack of separation between algorithms whose performance vary wildly in practice. In particular, when comparing two online algorithms we contrast their performance indirectly using the artifact of the off-line optimum. This leads to, in certain cases, unrealistic predictions of the actual observed behaviour of online algorithms. Many researchers in the field have observed these drawbacks and considered alternatives to the competitive ratio. In this talk we use paging as a case study on how to bridge the gap between theory and practice and extend these conclusions to on-line motion planning. We introduce the concept of cooperative ratio in which the "adversary" actively cooperates with the online algorithm in the construction of the input. This reflects the case of memory access in which programmers and compilers actively seek to minimize unnecessary paging. Similarly in motion planning in robotics in many cases the scene is designed by a friendly, cooperating agent such as an architect and interior designer and hence the worst case can be safely assumed not to occur. Optimal strategies under these assumptions can differ radically from those proposed under the competitive analysis framework.

Joint work of: Angelopoulos, Spyros; Dorrigiv, Reza; López-Ortiz, Alejandro; Munro, Ian

Self-Localisation and Route Learning in Mobile Robots Through System Identification

Ulrich Nehmzow (University of Essex, GB)

Navigational capabilities in mobile robots can be achieved through symbolic representations of the robot's environment and cognitive reasoning. They can, however, also be achieved through sub-symbolic sensor signal interpretation.

The RobotMODIC project at the Universities of Essex and Sheffield aims to develop a theory of robot-environment interaction that allows to analyse robot behaviour quantitatively, model behaviour through transparent mathematical functions, and to state formal hypotheses about robot behaviour (i.e. make predictions).

As part of this ongoing research, we investigate the relationship between perception and location/action, using transparent system identification techniques. By this method location or route learning ability are encoded as a one-line mathematical expression (a polynomial). The relationship between a robot's perception and its location, therefore, is established as a transparent mathematical function that can be analysed using methods such as analysis, sensitivity analysis or statistics.

This talk will present results of experiments conducted at Essex, in which a Magellan Pro mobile robot was successfully tested on self-localisation and route learning.

Keywords: Analytical robotics, robot modelling, localisation and route learning

Full Paper:
http://cswww.essex.ac.uk/staff/udfn/Quantitative/quantitative.html

See also: Ulrich Nehmzow, Scientific Methods in Mobile Robotics - Quantitative Analysis of Agent Behaviour, Springer Verlag 2006. ISBN: 1-84628-019-2

6D SLAM with Cached kd-tree Search

Andreas Nüchter (Universität Osnabrück, D)

6D SLAM (Simultaneous Localization and Mapping) or 6D Concurrent Localization and Mapping of mobile robots considers six degrees of freedom for the robot pose, namely, the x, y and z coordinates and the roll, yaw and pitch angles. In previous work we presented our scan matching based 6D SLAM approach, where scan matching is based on the well known iterative closest point (ICP) algorithm [Besl 1992]. Efficient implementations of this algorithm are a result of a fast computation of closest points. The usual approach, i.e., using kd-trees is extended in this paper. We describe a novel search strategy, that leads to significant speed-ups. Our mapping system is real-time capable, i.e., 3D maps are computed using the resources of the used Kurt3D robotic hardware.

Keywords: SLAM, kd tree search

Joint work of: Nüchter, Amdreas; Lingemann, Kai; Hertzberg, Joachim

Corridors – a New Paradigm for Path Planning

Mark Overmars (Utrecht University, NL)

Path planning plays an important role in many areas, not only in robotics but also in games and virtual environments.

Techniques like the Probabilistic Roadmap Method (PRM) are though not directly applicable to path planning problems in games. In games we need high quality (natural) paths. After preprocessing path queries should be answered in less that 1 millisecond. And the solution should be flexible enough to avoid other entities and small obstacles, to take constraints on the motion into account and to incorporate tactical constraints.

A new paradigm for path planning is suggested. In this approach we construct a high-quality roadmap of possible motions. The roadmap should be small and

have a high clearance. With each position on the roadmap, clearance information is stored in the form of the largest empty disk. During a query, a path is computed in the roadmap. The corresponding clearance information forms a corridor. An attraction point is moved along the path, attracting the moving entity. Using the correct forces, the path for the entity becomes smooth and always stays inside the corridor.

The approach is very flexible. It can handle additional small obstacles using repulsive forces or by locally adapting the corridor. Also it can handle the motion of groups of entities and tactical constraints can easily be integrated. And query times typically are far less than a millisecond, as required.

Keywords: Path planning, corridors, games

Intelligent Agents - providing a shortest paths service

Jörg-Rüdiger Sack (Carleton University - Ottawa, CA)

We discuss an agent-based framework aimed at providing access to, and support for the manipulation of, spatial information. It is designed as an open architecture which can accommodate a large number of mobile users and services possibly distributed across a wide geographical area. Today's users are mobile and are equipped with small powerful devices. Using wireless communication, these devices are/will be capable of exchanging digital data and voice from almost any location. In this talk, we present our architecture which is aimed at replacing a typically monolothical approach with a new dynamic, lean, and customizable system supporting spatially-oriented applications. Here, we present this vision, describe our design of the system. Finally, we discuss a sample shortest path service and report on some experimental results concerning shortest paths.

Keywords: Computational geometry, intelligent agents, systems, navigation, shortest paths

Polygon Exploration with Discrete Vision

Christiane Schmidt (TU Braunschweig, D)

With the advent of autonomous robots with two- and three-dimensional scanning capabilities, classical visibility-based exploration methods from computational geometry have gained in practical importance. However, real-life laser scanning of useful accuracy does not allow the robot to scan continuously while in motion; instead, it has to stop each time it surveys its environment. This requirement was studied by Fekete, Klein and Nüchter for the subproblem of looking around a corner, but until now has not been considered for whole polygonal regions.

We give the first comprehensive algorithmic study for this important algorithmic problem that combines stationary art gallery-type aspects with watchman-type issues in an online scenario. We show that there is a lower bound of $\Omega(\sqrt{n})$

on the competitive ratio in an orthogonal polygon with holes; we also demonstrate that even for orthoconvex polygons, a competitive strategy can only be achieved for limited aspect ratio A, i.e., for a given lower bound on the size of an edge. Our main result is an $O(\log A)$-competitive strategy for simple rectilinear polygons, which is best possible up to constants.

Keywords: Searching, scan cost, visibility problems, watchman problems, online searching, competitive strategies, autonomous mobile robots.

Joint work of: Fekete, Sándor; Schmidt, Christiane

Full Paper: http://drops.dagstuhl.de/opus/volltexte/2007/871

Extracting Visibility Information by Following Walls

Anna Yershova (Univ. of Illinois - Urbana, USA)

This paper presents an analysis of a simple robot model, called Bitbot. The Bitbot has limited capabilities; it can reliably follow walls and sense a contact with a wall. Although the Bitbot does not have a range sensor or a camera, it is able to acquire visibility information from the environment, which is then used to solve a pursuit-evasion task. Our developments are centered on the characterization of the information the Bitbot acquires. At any given moment, due to the sensing uncertainty, the robot does not know the current state. In general, uncertainty in the state is one of the central issues in robotics; the Bitbot model serves as an example of how the notion of information space naturally handles uncertainty. We show that state estimation with the Bitbot is a challenging problem, related to the well-known open problem of characterizing visibility graphs in computational geometry. However, state estimation becomes unnecessary to the achievement of the Bitbot's visibility tasks. We show how pursuit-evasion strategy is derived from a careful manipulation with histories of observations, and present analysis of the algorithm and experimental results.

Keywords: Planning, localization, pursuit evasion, visibility

Joint work of: Yershova, Anna; Tovar, Benjamín; LaValle, Steven M.

Computing Shortest Path amidst Growing Discs in the Plane

Jur van den Berg (Utrecht University, NL)

In this paper we discuss the problem of planning safe paths amidst unpredictably moving obstacles in the plane. Given the initial positions and the maximal velocities of the moving obstacles, the regions that are possibly not collision-free are modeled by discs that grow over time.

We present an approach to compute the shortest path between two points in the plane that avoids these growing discs. The generated paths are thus guaranteed to be collision-free with respect to the moving obstacles while being executed. We created a fast implementation that is capable of planning paths amidst many growing discs within milliseconds.

Keywords: Path planning dynamic environments

Joint work of: van den Berg, Jur; Overmars, Mark

Extended Abstract: http://drops.dagstuhl.de/opus/volltexte/2007/873

Full Paper:
http://www.cs.uu.nl/∼berg/WAFR2006-1.pdf

See also: Proc. Workshop on Algorithmic Foundations of Robotics - WAFR'06, 2006.