Time Optimal Trajectory Planning For Redundant Robots Joint Space Decomposition For Redundancy Resolution In Non Linear Optimization Bestmasters

This book deals with the problems related to planning motion laws and t- jectories for the actuation system of automatic machines, in particular for those based on electric drives, and robots. The problem of planning suitable trajectories is relevant not only for the proper use of these machines, in order to avoid undesired e?ects such as vibrations or even damages on the mech- ical structure, but also in some phases of their design and in the choice and sizing of the actuators. This is particularly true now that the concept of "el- tronic cams" has replaced, in the design of automatic machines, the classical approach based on "mechanical cams". The choice of a particular trajectory has direct and relevant implications on several aspects of the design and use of an automatic machine, like the dimensioning of the actuators and of the reduction gears, the vibrations and e?orts generated on the machine and on the load, the tracking errors during the motion execution. For these reasons, in order to understand and appreciate the peculiarities of the di?erent techniques available for trajectory planning, besides the ma- ematical aspects of their implementation also a detailed analysis in the time and frequency domains, a comparison of their main properties under di?erent points of view, and general considerations related to their practical use are reported.

Abstract: "Optimal trajectory planning problems are often formulated as constrained variational problems. In general, solutions to variational problems are determined by appropriately discretizing the underlying objective functional and solving the resulting nonlinear differential equation(s) and/or nonlinear programming problems(s) numerically. These general solution techniques often require a significant amount of time to be computed, and therefore are of limited value when optimal trajectories need to be frequently computed and/or re-computed. In this paper, a realistic class of optimal trajectory planning problems is defined for which the existence of fast numerical solution techniques are demonstrated. To illustrate the practicality of this class of trajectory planning problems and the proposed solution techniques, three optimal trajectory planning problems for spray coating applications are formulated and solved. Based on the proposed discretization technique, it is shown that these problems can be reduced to either a linear

program or a quadratic program, which are readily solved. In contrast, using the standard discretization of these problems generally leads to nonconvex nonlinear programming problems that require a sgnificant amount of computation to arrive at a (possibly) locally optimal solution."

Trajectory generation or motion planning is one of the critical steps in the control design for autonomous robots. The problem of shortest trajectory or time optimal trajectory has been a topic of active research. In this, thesis Sequential Linear Programming algorithm (SLP) and Global Local Mapping (Glomap) are the two methods used to solve the optimal trajectory generation problem for a differential drive robot. The time optimal path planning problem is posed as a linear programming problem which is solved using the SLP algorithm. In the Glomap approach the time domain is broken into smaller domains. The trajectory is generated for each local domain and then merged into a global trajectory. In both these methods potential functions are used to represent the obstacles in the configuration space. The trajectory generation methods are implemented in Matlab and validated on a robotic platform. Though the methods mentioned here are used for path planning for a differential drive robot they may be used for other systems with little or no modifications.

This paper addresses the problem of time-optional motions for a mobile platform in a planar environment. The platform has two non-steerable independently driven wheels. The overall mission of the robot is expressed in terms of a sequence of via points at which the platform must be at rest in a given configuration (position and orientation). The objective is to plan time-optimal trajectories between these configurations assuming an unobstructed environment. Using Pontryagin's maximum principle (PMP), we formally demonstrate that all time optimal motions of the platform for this problem occur for bang-bang controls on the wheels (at each instant, the acceleration on each wheel is either at its upper or lower limit). The PMP, however, only provides necessary conditions for time optimality. To find the time optimal robot trajectories, we first parameterize the bang-bang trajectories using the switch times on the wheels (the times at which the wheel accelerations change sign). With this parameterization, we can fully search the robot trajectory space and find the switch times that will produce particular paths to a desired final configuration of the platform. We show numerically that robot trajectories with three switch times (two on one wheel, one on the other) can reach any position, while trajectories with four switch times can reach any configuration. By numerical comparison with other trajectories involving

similar or greater numbers of switch times, we then identify the sets of time-optimal trajectories. These are uniquely defined using ranges of the parameters, and consist of subsets of trajectories with three switch times for the problem when the final orientation of the robot is not specified, and four switch times when a full final configuration is specified. We conclude with a description of the use of the method for trajectory planning for one of our robots.

Realtime Motion Planning for Manipulator Robots Under Dynamic Environments

Proceedings of the Twelfth Workshop on the Algorithmic Foundations of Robotics

Optimal trajectory planning of robots with parallel structure

Inverse Kinematics for Redundant Robots and Fast Solution of Parametric Problems

Optimal Path and Trajectory Planning for Serial Robots

Modern Robotics

Intelligent Unmanned Ground Vehicles describes the technology developed and the results obtained by the Carnegie Mellon Robotics Institute in the course of the DARPA Unmanned Ground Vehicle (UGV) project. The goal of this work was to equip off-road vehicles with computer-controlled, unmanned driving capabilities. The book describes contributions in the area of mobility for UGVs including: tools for assembling complex autonomous mobility systems; on-road and off-road navigation; sensing techniques; and route planning algorithms. In addition to basic mobility technology, the book covers a number of integrated systems demonstrated in the field in realistic scenarios. The approaches presented in this book can be applied to a wide range of mobile robotics applications, from automated passenger cars to planetary exploration, and construction and agricultural machines. Intelligent Unmanned Ground Vehicles shows the progress that was achieved during this program, from brittle specially-built robots operating under highly constrained conditions, to groups of modified commercial vehicles operating in tough environments. One measure of progress is how much of this technology is being used in other applications. For example, much of the work in road-following, architectures and obstacle detection has been the basis for the Automated Highway Systems (AHS) prototypes currently under development. AHS will lead to commercial prototypes within a few years. The cross-country technology is also being used in the development of

planetary rovers with a projected launch date within a few years. The architectural tools built under this program have been used in numerous applications, from an automated harvester to an autonomous excavator. The results reported in this work provide tools for further research development leading to practical, reliable and economical mobile robots.
This book constitutes the refereed proceedings of the 8th International Conference on Neural Networks and Artificial Intelligence, ICNNAI 2014, held in Brest, Belarus, in June 2014. The 19 revised full papers presented were carefully reviewed and selected from 27 submissions. The papers are organized in topical sections on forest resource management; artificial intelligence by neural networks; optimization; classification; fuzzy approach; machine intelligence; analytical approach; mobile robot; real world application.
Robot arms are used within their wok space to execute a variety of physical tasks like pick and place, or weld along a contour. From a robot control perspective, these tasks can be simply viewed as tasks of trajectory planning of the robot end effector. The path of the robot end effector is generally prescribed as a number of spatial points through which the end effector has to pass. A large number of approaches for the planning of the trajectory of a robot has been developed. These approaches do not generally allow adequate control over the acceleration profile of the trajectory. Furthermore, among those approaches only a few generate trajectories that are time optimal, and only for very simplistic robots. This work deals with yet another method for trajectory planning. The method allows full control over the acceleration profile so as to minimize the jerk at the beginning and end of the motion. The method also allows the utilization of the axes drive motors to their full capability in order to obtain a quasi-optimum trajectory that passes through all the points defining the end effector path. Simulation of the method for a three degrees of freedom revolute arm manipulator has been carried out. Results and discussion are presented in this study.
In this dissertation, we study two important subjects in robotics: (i) time-optimal trajectory planning, and (ii) optimal control synthesis methodologies for trajectory tracking. In the first subject, we concentrate on a rather specific sub-class of problems, the time-optimal trajectory planning along predetermined geometric paths. In this kind

of problem, a purely geometric path is already known, and the task is to find out how to move along this path in the shortest time physically possible. In order to generate the true fastest solutions achievable by the actual robot manipulator, the complete nonlinear dynamic model should be incorporated into the problem formulation as a constraint that must be satisfied by the generated trajectories and feedforward torques. This important problem was studied in the 1980s, with many related methods for addressing it based on the so-called velocity limit curve and variational methods. Modern formulations directly discretize the problem and obtain a large-scale mathematical optimization problem, which is a prominent approach to tackle optimal control problems that has gained popularity over variational methods, mainly because it allows to obtain numerical solutions for harder problems. We contribute to the referred problem of time-optimal trajectory planning, by extending and improving the existing mathematical optimization formulations. We successfully incorporate the complete nonlinear dynamic model, including viscous friction because for the fastest motions it becomes even more significant than Coulomb friction; of course, Coulomb friction is likewise accommodated for in our formulation. We develop a framework that guarantees exact dynamic feasibility of the generated time-optimal trajectories and feedforward torques. Our initial formulation is carefully crafted in a rather specific manner, so that it allows to naturally propose a convex relaxation that solves exactly the original problem formulation, which is non-convex and therefore hard to solve. In order to numerically solve the proposed formulation, a discretization scheme is also developed. Unlike traditional and modern formulations, we motivate the incorporation of additional criteria to our original formulation, with simulation and experimental studies of three crucial variables for a 6-axis industrial manipulator. Namely, the resulting applied torques, the readings of a 3-axis accelerometer mounted at the manipulator end-effector, and the detrimental effects on the tracking errors induced by pure time-optimal solutions. We therefore emphasize the significance of penalizing a measure of total jerk and of imposing acceleration constraints. These two criteria are incorporated without destroying convexity. The final formulation generates near time-optimal trajectories and feedforward torques with traveling times that are slightly larger than those of pure time-optimal solutions. Nevertheless, the detrimental effects induced by pure time-optimality are eliminated. Experimental results on a 6-axis industrial manipulator confirm that our formulation generates the fastest solutions that can actually be implemented in the real robot manipulator. Following the work done on near time-optimal trajectories, we explore two controller synthesis methodologies for trajectory tracking, which are more suitable to achieve trajectory-tracking under such fast trajectories. In the first approach, we approximate the discrete-time nonlinear dynamics of robot manipulators, moving along the state-reference trajectory, as an affine time-varying (ATV) dynamical system in discrete-time. Therefore, the problem of trajectory tracking for robot manipulators is posed as a linear quadratic (LQ) optimal control problem for a class of discrete-time ATV dynamical systems. Then, an ATV control law to achieve trajectory tracking on the ATV system is developed, which uses LQ methods for linear time-varying (LTV) systems. Since the ATV dynamical system approximates the nonlinear robot dynamics along the state-reference trajectory, the resulting time-varying control law is suitable to achieve trajectory tracking on the robot manipulator. The ATV control law is implemented in experiments for the 6-axis industrial manipulator, tracking the near time-optimal trajectory. Experimental results verify the better performance achieved with the ATV control law, but also expose its shortcomings. The second approach to address trajectory tracking is related in spirit, but different in crucial aspects, which ultimately endow this approach with its superior features. In this novel approach, the highly nonlinear dynamic model of robot manipulators, moving along a state-reference trajectory, is approximated as a class of piecewise affine (PWA) dynamical systems. We propose a framework to construct the referred PWA system, which consists in: (i) choosing strategic operating points on the state-reference trajectory with their respective (local) linearized system dynamics, (ii) constructing ellipsoidal regions centered at the operating points, whose purpose is to facilitate the scheduling strategy of controller gains designed for each local dynamics. Likewise, in order to switch controller gains as the robot state traverses in the direction of the state-reference trajectory, a simple scheduling strategy is proposed. The controller synthesis near each operating point is an LQR-type that takes into account the local coupled dynamics. The referred PWA control law is implemented in experiments for the 6-axis manipulator tracking the near time-optimal trajectory. The experimental results show the feasibility and superiority of the PWA control law over the typical PID controller and the ATV control law.

On the Time-optimal Trajectory Planning Along Predetermined Geometric Paths and Optimal Control Synthesis for Trajectory Tracking of Robot Manipulators

Time-Energy Optimal Cluster Space Motion Planning for Mobile Robot Formations

Primal-dual Interior-Point Methods

Time-Optimal Trajectory Planning for Redundant Robots

Advances in Robot Kinematics: Analysis and Design

Time Optimal Trajectories for Mobile Robots with Two Independently Driven Wheels

Machine automation requires the robotic machine to be at least as productive as a manually operated machine. To increase robot productivity robot motion speed should be improved. A feasible approach to improving the motion speed is to minimize the motion time needed to perform a given task subject to actuator constraints. This work addresses the problem of optimal trajectory planning for heavy-duty hydraulic manipulators. These manipulators have the following characteristics: they are powered by a single engine mounted on the machine and they are under-powered even during normal operations resulting in dynamic power redistribution to the actuators. For the hydraulic manipulators, the actuator characteristics are very significant and complex due to high nonliniarities in the hydraulic system and power coupling between the actuators. The method developed in this thesis focuses on utilizing advantageously the actuator capabilities to minimize the time needed to move the manipulator end-effector along a specified path. To perform the search for the minimum motion time along the specified path, a downhill simplex technique is implemented. The method is applied to a Caterpillar 215B excavator-based log loader in a typical pick and place task. The main contributions of thi thesis are the incorporation of the complex actuator characteristics in the optimal trajectory planning and the

implementation of an optimization algorithm (downhill simplex method), which shows effective results for solving the optimal trajectory planning problem.
Planning algorithms are impacting technical disciplines and industries around the world, including robotics, computer-aided design, manufacturing, computer graphics, aerospace applications, drug design, and protein folding. This coherent and comprehensive book unifies material from several sources, including robotics, control theory, artificial intelligence, and algorithms. The treatment is centered on robot motion planning, but integrates material on planning in discrete spaces. A major part of the book is devoted to planning under uncertainty, including decision theory, Markov decision processes, and information spaces, which are the 'configuration spaces' of all sensor-based planning problems. The last part of the book delves into planning under differential constraints that arise when automating the motions of virtually any mechanical system. This text and reference is intended for students, engineers, and researchers in robotics, artificial intelligence, and control theory as well as computer graphics, algorithms, and computational biology.
While rovers have traditionally been used to explore extraterrestrial bodies, they reduce the total area explored on the ground as they are limited by traversing the surface. For this reason vertical takeoff and landing crafts are explored. The major downfall of this type of craft for exploration is the extra fuel costs which must be carried into orbit. Reducing the fuel burn for a given maneuver allows the mission to either bring less propellant or to explore further. In either case, it is highly advantageous to reach destination points with the least amount of fuel. This paper looks at fuel-optimal trajectory planning for these reasons. A combination of optimal control theory with sequential quadratic programming and rapidly exploring random trees is proposed to achieve a robust, real time optimal trajectory.
This master's thesis presents a novel approach to finding trajectories with minimal end time for kinematically redundant manipulators. Emphasis is given to a general applicability of the developed method to industrial tasks such as gluing or welding. Minimum-time trajectories may yield economic advantages as a shorter trajectory duration

results in a lower task cycle time. Whereas kinematically redundant manipulators possess increased dexterity, compared to conventional non-redundant manipulators, their inverse kinematics is not unique and requires further treatment. In this work a joint space decomposition approach is introduced that takes advantage of the closed form inverse kinematics solution of non-redundant robots. Kinematic redundancy can be fully exploited to achieve minimum-time trajectories for prescribed end-effector paths.

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Real-time Trajectory Planning for Ground and Aerial Vehicles in a Dynamic Environment

Optimal Trajectory Planning for Mobile Robots

Dynamic Model Based Time Optimal Trajectory Planning and Control of Motion for Robotic Manipulators

Time-optimal Trajectory and Path Planning on Industrial Robots

Time Optimal Trajectory Planning and Control for a Robot

Alexander Reiter describes optimal path and trajectory planning for serial robots in general, and rigorously treats the challenging application of path tracking for kinematically redundant manipulators therein in particular. This is facilitated by resolving both the path tracking task and the optimal inverse kinematics problem simultaneously. Furthermore, the author presents methods for fast computation of approximate optimal solutions to planning problems with changing parameters. With an optimal solution to a nominal problem, an iterative process based on parametric sensitivities is applied to rapidly obtain an approximate solution. About the Author: Dr. Alexander Reiter is a senior scientist at the Institute of Robotics of the Johannes Kepler University (JKU) Linz, Austria. His major fields of research are kinematics, dynamics, and trajectory planning for kinematically redundant serial robots as well as real-time methods for solving parametric non-linear programming problems. Real-time optimal trajectory design and tracking for autonomous ground vehicles are maturing technologies with the potential to advance mobility by enhancing time and energy efficiency in application such as indoor surveillance robots or planetary exploration rovers. Pseudo-spectral methods based trajectory generation framework provides the desired trajectory which minimizes a prescribed objective function (i.e. minimum time, acceleration, and energy) while satisfying kinodynamics and various types of constraints (i.e. obstacle avoidance and smooth turning at waypoint transitions). In this thesis cyber-physical system architecture is used for the communication between rover-vehicle and the ground station. By using optimal state and control vector from trajectory generation module and by obtaining the state feedback values from the

cyber-physical system architecture, a backstepping based controller provides commanded control values to complete the trajectory. Combination of novel optimal trajectory framework (Guidance), modified backstepping controller (control) and cyber-physical system architecture makes the complete guidance navigation and control system. This thesis work elaborates, the efficacy of the overall approach by performing several experimental test runs carried out with the rover vehicle equipped with GPS, compass, and wheel encoders.

The study proposed and demonstrated a strategy smooth trajectory planning to follow the path constrained with time optimal trajectories for the manipulator. The problem in trajectory planning was to find a smooth trajectory function and optimal joint optimisation processes. Such trajectories were obtained by considering the kinem~tics properties for velocities, accelerations and jerks profiles in joint coordi~!ites for the end-effector to move the path constraints. The method was based on the position profile composed of three polynomial segments such as 4-3-4, 3-5-3 and 3-cubic trajectory and five polynomial segments for 5-cubic trajectory. These polynomial segments combination allowed the analytical solution to the minimum time trajectory problem under consideration of velocity, acceleration and jerk by using Mathematica software. A number of simulations were performed to demonstrate the trajectory methods using robot simulation PUMA 560 model. The robot simulation model was developed using Mechanical Desktop software and the analytical analysis was done USIng visualNastran software. The simulations showed that the trajectory ability methods for the investigation under varying time ratio conditions and the operations such as Pick and Place Operation (PPO) and Continuous Path (CP). For comparison on varying time ratio 4-3-4 gave a reasonably smooth for normal trajectory condition and a ramp at middle segment to generate a minimum free-space time compared to 3-5-3 and cubic trajectories. For PPO and CP, 4-3-4 trajectory generated a lower values for accelerations and jerks compared to 3-5-3 and cubic trajectories. This showed the 4-3-4 trajectory was the best type of joint interpolated trajectory planning for any path planning operations.

A modern and unified treatment of the mechanics, planning, and control of robots, suitable for a first course in robotics.

Robot Manipulator Redundancy Resolution

Trajectory Planning for Automatic Machines and Robots

Motion and Operation Planning of Robotic Systems

An Optimal Control Approach

Advances in Engineering Research and Application

A provably good approximation algorithm for optimal-time trajectory planning

Laser drilling provides a highly productive method for producing arrays of holes on planar and freeform shaped components. Industrial applications include fuel injection nozzles, printed circuit boards (PCB's), inkjet printer *heads, pinholes and slits for scientific instrumentation, high-resolution circuitry, sensors, fiber-optic interconnects, medical devices, and gas turbine combustion chamber panels. This thesis deals with time-optimal trajectory planning for two mainstream laser drilling methods: on-the-fly drilling and percussion drilling, which are used in the aerospace industry. The research has been conducted in collaboration with the Canadian aero-engine producer, Pratt & Whitney Canada (P&WC). The algorithms developed have been tested in a target application involving the laser drilling of cooling hole arrays on gas turbine engine combustion chamber panels. On-the-fly drilling is an operation in which each hole receives one low powered shot at a time while the workpiece is in motion, and the beam focal point is continuously proceeding to the next hole location. The positioning sequence repeats itself until all holes are gradually opened up in small increments. Each hole location has ample time to cool down before the next shot is received. Thus, this process can yield favorable material properties in terms of preserving the desired crystal structure, and also hole quality in terms of dimensional (size) and form (shape) accuracy, due to the reduction of local thermal loading. However, there is no existing trajectory planner, in industry, or in literature, capable of generating time-optimized positioning trajectories for on-the-fly laser drilling. This thesis studies this problem and presents a new algorithm, capable of handling 5 degree-of-freedom (axis) positioning capability. The ability to generate spline-based smooth trajectories is integrated within a Traveling Salesman Problem (TSP) type sequencing algorithm. The sequencing algorithm optimizes both the order of the waypoints (i.e., hole locations) and also the timing levels in between, which affect the temporal (time-dependent) nature of the motions commanded to the laser drilling machine's actuators. Furthermore, the duration between consecutive holes has to be an integer multiple of the laser pulsing period, considering a machine configuration in which the laser is firing at a constant frequency, and unused pulses are diverted away using a quick shutter. It is shown that the proposed algorithm is capable of generating 17-25% reduction in the beam positioning time spent during a manufacturing cycle, compared to some of the contemporary practices in industry. 17% reduction in the* *vibrations induced onto the laser optics is also observed, which helps prevent downtime due to the optics hardware gradually losing alignment. The second type of laser drilling operation for which optimized 5-axis trajectory planning has been developed is percussion drilling. In this process, a series of pulses are sent to each hole while the part is stationary. Once the hole is completely opened up, then positioning to the next hole proceeds. While percussion drilling is less advantageous in terms of local thermal loading and achievable part quality, it is used extensively in industry; due to its simplicity of automation compared to on-the-fly drilling. Thus, a TSP-style trajectory planning algorithm has also been developed for percussion laser drilling. The novelty, in this case, is concurrent planning of 5-axis time-optimal point-to-point movements within the sequencing algorithm, and direct minimization of the total travel time, rather than just distance (in two Cartesian axes); as is the method for which significant portion of TSP solvers and trajectory planners in literature have been developed. Compared to currently applied methods at P&WC, 32-36% reduction in the beam positioning time has been achieved. Also, 39-45% reduction in the peak magnitude of vibration has been realized. Limited benchmarking with state-of-the-art TSP solvers from combinatorial mathematics, considering only 2-axis Euclidean distance as the objective function, indicate that the proposed sequencing algorithm for percussion drilling is sub-optimal by 9-12%. Thus, it can still use further improvement in future research. Nevertheless, the two trajectory planners that have been developed in this thesis for on-the-fly drilling and percussion drilling have experimentally demonstrated very promising improvements in terms of motion time and smoothness. As more advanced Computer Numerical Control (CNC) systems and laser control electronics with deterministic execution and rapid synchronization capability become available, such algorithms are expected to facilitate significant production gains in laser drilling processes used in different industries.*

We consider the following problem: given a robot system, find a minimal-time trajectory from a start position and velocity to a goal position and velocity, while avoiding obstacles and respecting dynamic constraints on velocity and acceleration. Based on the theoretical results of [CDRX], we *have developed and implemented a new, provably good approximation algorithm for the minimum-time trajectory problem. Our algorithm differs from previous work in three ways. First, it is possible to bound the goodness of the approximation by an error term ϵ. Second, we can polynomially bound the running time (complexity) of our algorithm. Third, we can express the complexity as a polynomial function of the error term. Hence, one supplies the algorithm with the geometric obstacles, dynamics bounds, and the error term ϵ. The algorithm returns a solution that is ϵ-close to optimal, and promises to spend only a polynomial (in $(\frac{1}{\epsilon})$) amount to time computing the answer. In this paper, we describe the algorithm and explain the results in simple terms. We show how it can be applied to robotics, and report on an implementation and experiments.*

In the past decade, primal-dual algorithms have emerged as the most important and useful algorithms from the interior-point class. This book presents the major primal-dual algorithms for linear programming in straightforward terms. A thorough description of the theoretical properties of these methods is given, as are a discussion of practical and computational aspects and a summary of current software. This is an excellent, timely, and well-written work. The major primal-dual algorithms covered in this book are path-following algorithms (short- and long-step, predictor-corrector), potential-reduction algorithms, and infeasible-interior-point algorithms. A unified treatment of superlinear convergence, finite termination, and detection of infeasible problems is presented. Issues relevant to practical implementation are also discussed, including sparse linear algebra and a complete specification of Mehrotra's predictor-corrector algorithm. Also treated are extensions of primal-dual algorithms to more general problems such as monotone complementarity, semidefinite programming, and general convex programming problems.

This book addresses the broad multi-disciplinary topic of robotics, and presents the basic techniques for motion and operation planning in robotics systems. Gathering contributions from experts in diverse and wide ranging fields, it offers an overview of the most recent and cutting-edge practical applications of these methodologies. It covers both theoretical and practical approaches, and *elucidates the transition from theory to implementation. An extensive analysis is provided, including humanoids, manipulators, aerial robots and ground mobile robots. 'Motion and Operation Planning of Robotic Systems' addresses the following topics: *The theoretical background of robotics. *Application of motion planning techniques to manipulators, such as serial and parallel manipulators. *Mobile robots planning, including robotic applications related to aerial robots, large scale robots and traditional wheeled robots. *Motion planning for humanoid robots. An invaluable reference text for graduate students and researchers in robotics, this book is also intended for researchers studying robotics control design, user interfaces, modelling, simulation, sensors, humanoid robotics.*

Time Optimal Trajectory Planning for Mobile Manipulators

Basic Concepts for Instantaneous Reactions to Unforeseen (Sensor) Events

Practical Methods for Optimal Control Using Nonlinear Programming, Third Edition

Optimal Trajectory Planning for Hydraulic Manipulators with Power Limitations

Fidelity of Flight Control Systems in a Real-time Optimal Trajectory Planner

Intelligent Unmanned Ground Vehicles

This book presents the outcomes of the 12th International Workshop on the Algorithmic Foundations of Robotics (WAFR 2016). WAFR is a prestigious, single-track, biennial international meeting devoted to recent advances in algorithmic problems in robotics. Robot algorithms are an important building block of robotic systems and are used to process inputs from users and sensors, perceive and build models of the environment, plan low-level motions and high-level tasks, control robotic actuators, and coordinate actions across multiple systems. However, developing and analyzing these algorithms raises complex challenges, both theoretical and practical. Advances in the algorithmic foundations of robotics have applications to manufacturing, medicine, distributed robotics, human–robot interaction, intelligent prosthetics, computer animation, computational biology, and many other areas. The 2016 edition of WAFR went back to its roots and was held in San Francisco, California – the city where the very first WAFR was held in 1994. Organized by Pieter Abbeel, Kostas Bekris, Ken Goldberg, and Lauren Miller, WAFR 2016 featured keynote talks by John Canny on "A Guided Tour of Computer Vision, Robotics, Algebra, and HCI," Erik Demaine on "Replicators, Transformers, and Robot Swarms: Science Fiction through Geometric Algorithms," Dan Halperin on "From Piano Movers to Piano Printers: Computing

and Using Minkowski Sums," and by Lydia Kavraki on "20 Years of Sampling Robot Motion." Furthermore, it included an Open Problems Session organized by Ron Alterovitz, Florian Pokorny, and Jur van den Berg. There were 58 paper presentations during the three-day event. The organizers would like to thank the authors for their work and contributions, the reviewers for ensuring the high quality of the meeting, the WAFR Steering Committee led by Nancy Amato as well as WAFR's fiscal sponsor, the International Federation of Robotics Research (IFRR), led by Oussama Khatib and Henrik Christensen. WAFR 2016 was an enjoyable and memorable event.
How do you fly an airplane from one point to another as fast as possible? What is the best way to administer a vaccine to fight the harmful effects of disease? What is the most efficient way to produce a chemical substance? This book presents practical methods for solving real optimal control problems such as these. Practical Methods for Optimal Control Using Nonlinear Programming, Third Edition focuses on the direct transcription method for optimal control. It features a summary of relevant material in constrained optimization, including nonlinear programming; discretization techniques appropriate for ordinary differential equations and differential-algebraic equations; and several examples and descriptions of computational algorithm formulations that implement this discretize-then-optimize strategy. The third edition has been thoroughly updated and includes new material on implicit Runge–Kutta discretization techniques, new chapters on partial differential equations and delay equations, and more than 70 test problems and open source FORTRAN code for all of the problems. This book will be valuable for academic and industrial research and development in optimal control theory and applications. It is appropriate as a primary or supplementary text for advanced undergraduate and graduate students.
Time-Optimal Trajectory Planning for Redundant RobotsJoint Space Decomposition for Redundancy Resolution in Non-Linear OptimizationSpringer
This report presents optimal control methods integrated with hierarchical control framework to realize real-time collision-free optimal trajectories for motion control in kinematic chain manipulator (KCM) robot systems under dynamic environments. Recently, they have been increasingly used in applications where manipulators are required to interact with random objects and humans. As a result, more complex trajectory planning schemes are required. The main objective of this research is to develop new motion control strategies that can enable such robots to operate efficiently and optimally in such unknown and dynamic environments. Two direct optimal control methods: The direct collocation method and discrete mechanics for optimal control methods are investigated for solving the related constrained optimal control problem and the results are compared. Using the receding horizon control structure, open-loop sub-optimal trajectories are generated as real-time input to the controller as opposed to the predefined trajectory over the entire time duration. This, in essence, captures the dynamic nature of the obstacles. The closed-loop position controller is then

engaged to span the robot end-effector along this desired optimal path by computing appropriate torque commands for the joint actuators. Employing a two-degree of freedom technique, collision-free trajectories and robot environment information are transmitted in real-time by the aid of a bidirectional connectionless datagram transfer. A hierarchical network control platform is designed to condition triggering of precedent activities between a dedicated machine computing the optimal trajectory and the real-time computer running a low-level controller. Experimental results on a 2-link planar robot are presented to validate the main ideas. Real-time implementation of collision-free workspace trajectory control is achieved for cases where obstacles are arbitrarily changing in the robot workspace.

Planning Algorithms

Neural Networks and Artificial Intelligence

Background and Practical Approaches

Time Optimal Trajectory Generation for a Differential Drive Robot

Fast Solution Techniques for a Class of Optimal Trajectory Planning Problems with Applications to Automated Spray Coating

Algorithmic Foundations of Robotics XII

The motions of a formation of mobile robots along predetermined paths are optimized according to a tunable time-energy cost function using the cluster space approach to multiagent system specification and control. Upon path-parameterizing cluster state variables describing the geometry and pose of a multirobot group, an optimal control problem is formulated that incorporates formation dynamics and state constraints. The optimal trajectory is derived numerically via a gradient search, iterating over the initial value of one costate. A multirobot formation control simulation is then used to demonstrate the effectiveness of the technique. Results indicate that a substantial tradeoff is made between energy expenditure and motion time when considered as minimization criteria in varying proportions, allowing the operator to tailor mission trajectories according to desired levels of each.

Introduces a revolutionary, quadratic-programming based approach to solving long-standing problems in motion planning and control of redundant manipulators This book describes a novel quadratic programming approach to solving redundancy resolutions problems with redundant manipulators. Known as ``QP-unified motion planning and control of redundant manipulators'' theory, it systematically solves difficult optimization problems of inequality-constrained motion planning and control of redundant manipulators that have plagued robotics engineers and systems designers for more than a quarter century. An example of redundancy resolution could involve a robotic limb with six joints, or degrees of freedom (DOFs), with which to position an object. As only five numbers are required to specify the position and orientation of the object, the robot can move with one remaining DOF through practically infinite poses while performing a specified task. In this case redundancy resolution refers to the process of choosing an optimal pose from among that infinite set. A critical issue in robotic systems control, the redundancy

resolution problem has been widely studied for decades, and numerous solutions have been proposed. This book investigates various approaches to motion planning and control of redundant robot manipulators and describes the most successful strategy thus far developed for resolving redundancy resolution problems. Provides a fully connected, systematic, methodological, consecutive, and easy approach to solving redundancy resolution problems Describes a new approach to the time-varying Jacobian matrix pseudoinversion, applied to the redundant-manipulator kinematic control Introduces The QP-based unification of robots' redundancy resolution Illustrates the effectiveness of the methods presented using a large number of computer simulation results based on PUMA560, PA10, and planar robot manipulators Provides technical details for all schemes and solvers presented, for readers to adopt and customize them for specific industrial applications Robot Manipulator Redundancy Resolution is must-reading for advanced undergraduates and graduate students of robotics, mechatronics, mechanical engineering, tracking control, neural dynamics/neural networks, numerical algorithms, computation and optimization, simulation and modelling, analog, and digital circuits. It is also a valuable working resource for practicing robotics engineers and systems designers and industrial researchers.
Abstract: Given growing emphasis on robot autonomy, the problem of planning a trajectory for these autonomous systems in a complex environment has become increasingly important. The objective of this research is to solve trajectory generation and optimization problems for mobile robot systems with both single and multiple goals. Considering the complexity of general trajectory planning problems, we concentrate mainly on two dynamic models: a holonomic system where velocity is a control variable and a nonholonomic system proposed by Dubins with constant velocity and constrained turning radius. For the simple holonomic model, we focus on computation of optimal trajectories with complex objective functions. We use a stochastic control framework to obtain characterizations of optimal trajectories as solutions of Hamilton-Jacobi-Bellman equations. Based on either upwind schemes or value iteration methods, we develop and evaluate alternative numerical methods for both isotropic (velocity-independent) and anisotropic (velocity-dependent) cost models. For the Dubins' vehicle model, we extend the results of Dubins and others to solve for minimum-time trajectories with diverse path and terminal constraints, characterizing solutions using Pontryagin's Maximum Principle. A direct application of these local shortest-path solutions is the Dubins' Traveling Salesman problem (DTSP), where the goal is to find the shortest trajectory for a Dubins' vehicle given a number of locations. We extend our analytic solutions to two-point and three-point Dubins' shortest path problems to obtain a receding horizon algorithm that outperforms alternative algorithms proposed in the literature when the visiting order is known. We also combine these algorithms with existing TSP heuristics to obtain improved algorithms when the order is not known. We also studied trajectory planning for Dubins' vehicles in the presence of moving obstacles. For stationary obstacles and holonomic vehicles, probabilistic algorithms such as rapidly-

exploring random trees (RRTs) can provide guarantees of finding a path to a goal. We developed a variation of RRTs for time-varying obstacles and Dubins' dynamics. We prove probabilistic completeness for this algorithm, establishing that a path will be found if one exists. We also compared our approach with an alternative, the probabilistic roadmap algorithm, and established that our algorithm yields improvements for these problems.

Manipuladores paralelos são de grande interesse principalmente porque apresentam vantagens em várias aplicações, mostrando grande resistência, exatidão de posicionamento, capacidade de carga maior que manipuladores seriais e podem ser operados a altasvelocidades e acelerações. No Laboratório de Robótica e Mecatrônica em Cassino, Itália, foi criado um mecanismo paralelo com três graus de liberdade, chamado CaPaMan (Cassino Parallel Manipulator). O objetivo principal deste trabalho é otimizar a trajetória da estrutura paralela CaPaMan. O problema de otimização multi-objetivo considera a minimização da energia gasta pelos atuadores, do tempo total de percurso e da variação de aceleração (jerk). A trajetória é calculada assumindo que os ângulos de entrada são obtidos por uma função do tempo, representada por B-splines uniformes. A modelagem cinemática é obtida derivando-sea equação da trajetória em relação ao tempo. O modelo analítico para a dinâmica inversa do CaPaMan utiliza as equações de Newton-Euler. A cadeia cinemática peculiar e aspropriedades de simetria da arquitetura do CaPaMan são úteis nesta formulação, permitindo, para cada trajetória, calcular os torques de entrada e a energia dos atuadores. O vetor defunções multi-objetivo é transformado em uma função escalar usando o Método da Ponderação dos Objetivos. O problema de otimização é investigado aplicando algoritmos genéticos. Apresença de mínimos locais justifica a utilização de métodos randômicos. Alguns exemplos numéricos são apresentados para verificação e validação da metodologia proposta.

Time-optimal Trajectory Planning for Sequential Robotic Tasks with Unfixed Endpoints

Fuel-Optimal Trajectory Planning of a VTOL Spacecraft Using SQP and RRT.

Joint Space Decomposition for Redundancy Resolution in Non-Linear Optimization

Robot Manipulation Trajectory Planning in Complex Position

A Method for Generating a Controllable and Quasi Time Optimal Robot Trajectory

Autonomous Navigation Research at Carnegie Mellon

This proceedings volume gathers the outcomes of the International Conference on Engineering Research and Applications (ICERA 2019), which was held at Thai Nguyen University of Technology, Vietnam, on December 1-2, 2019 and provided an international forum for disseminating the latest theories and practices in engineering research and applications. The conference focused on original research work in a broad range of areas, including Mechanical Engineering, Materials and Mechanics of Materials, Mechatronics and Micromechatronics, Automotive Engineering, Electrical and Electronics Engineering, and Information and Communication Technology. By sharing the latest advances in these fields, the book will help academics and professionals alike to revisit their thinking on sustainable development.

In this dissertation, a novel and generic solution of trajectory generation is developed and evaluated for ground and aerial vehicles in a dynamic environment. By explicitly considering a kinematic model of the ground vehicles, the family of feasible trajectories and their corresponding steering controls are derived in a closed form and are expressed in terms of one adjustable parameter for the purpose of collision avoidance. A collision-avoidance condition is developed for the dynamically changing environment, which consists of a time criterion and a geometrical criterion. By imposing this condition, one can determine a family of collision-free paths in a closed form. Then, optimization problems with respect to different performance indices are setup to obtain optimal solutions from the feasible trajectories. Among these solutions, one with respect to the near-shortest distance and another with respect to the near-minimal control energy are analytical and simple. These properties make them good choices for real-time trajectory planning. Such optimal paths meet all boundary conditions, are twice differentiable, and can be updated in real time once a change in the environment is detected. Then this novel method is extended to 3D space to find a real-time optimal path for aerial vehicles. After that, to reflect the real applications, obstacles are classified to two types: "hard" obstacles that must be avoided, and "soft" obstacles that can be run over/through. Moreover, without losing generality, avoidance criteria are extended to obstacles with any geometric shapes. This dissertation also points out that the emphases of the future work are to consider other constraints such as the bounded velocity and so on. The proposed method is illustrated by computer simulations.

By the dawn of the new millennium, robotics has undergone a major tra- formation in scope and dimensions. This expansion has been brought about bythematurityofthe?eldandtheadvancesinitsrelatedtechnologies.From a largely dominant industrial focus, robotics has been rapidly expanding into the challenges of the human world. The new generation of robots is expected to safely and dependably co-habitat with humans in homes, workplaces, and communities,providingsupportinservices,entertainment,education,heal- care, manufacturing, and assistance. Beyond its impact on physical robots, the body of knowledge robotics has produced is revealing a much wider range of applications reaching across - verse research areas and scienti?c disciplines, such as: biomechanics, haptics, neurosciences, virtual simulation, animation, surgery, and sensor networks among others. In return, the challenges of the new emerging areas are pr- ing an abundant source of stimulation and insights for the ?eld of robotics. It is indeed at the intersection of disciplines that the most striking advances happen. The goal of the series of Springer Tracts in Advanced Robotics (STAR) is to bring, in a timely fashion, the latest advances and developments in robotics on the basis of their signi?cance and quality. It is our hope that the wider dissemination of research developments will stimulate more exchanges and collaborations among the research community and contribute to further advancement of this rapidly growing ?eld.

This book presents the most recent research advances in the theory, design, control and application of robotic systems, which are intended for a variety of purposes such as manipulation, manufacturing, automation, surgery, locomotion and biomechanics.

Dynamic model based time optimal trajectory planning and control of motion for robotic manipulators. 91/28

A Provable Good Approximation for Optimal-time Trajectory Planning

Proceedings of the International Conference on Engineering Research and Applications, ICERA 2019

Pseudo-spectral Methods Based Real-time Optimal Path Planning for Unmanned Ground Vehicles

8th International Conference, ICNNAI 2014, Brest, Belarus, June 3-6, 2014. Proceedings