MATHEMATISCHES FORSCHUNGSINSTITUT OBERWOLFACH

Tagungsbericht 26/1991

Mathematical Problems in Robotics

16.06.1991 bis 22.06.1991

The meeting was being organized by H. G. Bock (Augsburg), R. W. Longman (New York), and F. Pfeiffer (München). The participants were 34 mathematicians, engineers and computer scientists from 10 countries, 26 of which presented a lecture (sometimes including a video or computer graphics demonstration).

Advanced industrial robot operation planning calls for off-line programming and optimization in a CAD/CAM environment. This requires

- detailed, realistic modeling of kinematics and dynamics,
- mathematical description and analysis of the models,
- efficient numerical treatment.

Since the resulting mathematical problems are highly complex (like the robotic systems themselves), enforced interdisciplinary cooperation is necessary.

The intention of the meeting was to bring together scientists from various fields in robotics in order to gain an overview of presently important problems, find their relations to different research areas, establish connections between these areas, and finally exchange and develop solution approaches.

Topics of the presentations were in the fields of

- theoretical foundations: algebraic and differential geometry (of the Euclidian group SE(3) and its subgroup SO(3), in particular), holonomic and nonholonomic mechanics,
- modeling and mathematical description: impact, friction and contact phenomena, flexibility, back-lash, model identification from experiment data, classical and recursive formalisms for multibody systems, differential-algebraic formulation of dynamics, closed kinematic loops,
- advanced applications and optimal control: multi-arm robots, space based robotics, sensing, automatic decision-making, learning control, position and force control, open-loop and feedback control, minimum time and minimum energy trajectory planning (for prescribed-path and point-to-point maneuvers), collision avoidance.

Many of the presentations were closely related to specific practical applications or experiments; a central issue was usually the development of efficient and robust numerical methods and their implementation in 'real life'. Basic mathematical concepts not yet mentioned are, e.g., ordinary differential equations on Riemannian manifolds as dynamic models of multibody systems, including state-dependent sets of algebraic conditions and discontinuities in the right-hand side due to the listed physical effects, closed loops and multiple arms, further PDE or stochastic modeling

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due to link flexibility or parameter uncertainties, resp., and, in the context of model identification or trajectory planning, constrained optimization problems, which are possibly over- or underdetermined, unstable or ill-posed, and which may possess multiple local optima.
The thematic bandwidth was only natural, because almost any problem in robotics involves several of the concepts listed above. Therefore it was rather positive that the schedule left plenty of time for intensive discussions in small groups. Also, the pleasent atmosphere encouraged the mathematicians to look at a problem with an engineer's eyes, and vice versa. A lively exchange of ideas and viewpoints developed, which is likely to further stimulate the highly dynamic development in the robotics area.

Vortragsauszüge

Guillermo RODRIGUEZ
Spatial Operators for Robot Mathematical Modeling
The paper reviews the current status of spatially recursive methods for robot dynamics developed by the author in the last several years. The methods are based on an analogy between robot dynamics and state estimation theory. The methods generalize the equations of Kalman filtering and smoothing, quite popular in discrete time optimal estimation and control, to describe spatially recursive operations. This allows solution of robot dynamics problems within the highly developed state space filtering and smoothing architecture. The analogy also allows development of two alternative mass matrix factorizations: $M = H\Phi M\Phi^* H^*$ and $M = H(I+H\Phi G)D(I+H\Phi G)^*$. The first embedds within it several highly efficient algorithms for inverse dynamics and for recursive evaluation of the mass matrix. In particular, it contains the highly popular recursive Newton Euler algorithm for inverse dynamics. For this reason, the factorization is referred to as the Recursive Newton-Euler factorization. The second factorization is referred to as the innovations factorization, because of similarities with the innovations approach of linear least-squares filtering theory. Inversion of the mass matrix is readily achieved by inversion of the lower triangular factor $(I + H\Phi G)$ and the upper triangular factor $(I + H\Phi G)^*$. Inversion of the factors is achieved by spatially recursive filtering and smoothing. Inversion of the diagonal matrix D is achieved by inversion of its scalar elements. Development of these results is made possible by the use of spatial operators, such as Φ and Ψ, which govern the propagation of accelerations, forces, and velocities along the span of the robot. Analysis and computer programming is made simple because the spatial operators represent a large number of more detailed computational operations.

Suguru ARIMOTO
Passivity of Robot Dynamics and Its Role in Learning for Skill Refinement
Learning control is a new approach to the problem of skill refinement for robot arms by iterative training. It is considered to be a mathematical model of motor program learning for skilled motions in the central nervous system. In the talk a class of learning control algorithms with a forgetting factor $1>>\alpha>0$ and without differentiation of velocity signals is presented, which updates the input command by $u_{k+1} = (1-\alpha)\, u_k + \alpha u_0 + \phi e_k$, where u_k and e_k stand for command input and velocity error at k-th exercise respectively. The robustness of this learning control with respect to re-

initialization errors, fluctuations of robot dynamics, and measurement noises is analyzed in detail. It is shown that not only the passivity of robot dynamics but also the exponential passivity of displacement dynamics on errors and difference dynamics between consecutive trials play a crucial role in proving the uniform boundedness of transient behaviors and the convergence in the progress of learning.

Hartmut BREMER

Elastic Multibody Systems, Optimization and Control

Robots consisting of an arbitrary number of elastic links and flexible joints are considered which undergo a gross rigid body motion with superimposed small deflections. Linearisation of the latter requires the computation of second order terms, whose influence is often referred to as "Dynamical Stiffening". The Mathematical Description of such complex systems requires an adequate procedure to get the equations of motion with minimum effort.

Karim TAHBOUB

Descriptor Models for Constrained Robots in Assembly and Machining tasks

There are numerous applications where the end effector of a robot manipulator comes in contact with a rigid external object. These applications include the use of manipulators for carrying out assembling and machining tasks. In this talk, the modeling of the contact forces between the end effector of a robot and an external body is considered; the descriptor model is examined in depth. The task oriented modeling method is presented; this method introduces the task space as the starting point in finding the kinematic constraints which cover a large class of tasks including machining and assembly. A general and easy reduction method, in the task space, is as well presented to end up with explicit equations for the constraint forces and for the minimal number of acceleration variables. The reduced descriptor model with index one is accordingly derived, where it is composed of two subsystems; a slow subsystem corresponding to the minimal differential variables and a fast subsystem corresponding to the constraint forces. Due to the above mentioned reduction, it is to be noted that the fast subsystem does not contain any differential variables.

Gregory D. HAGER

Towards Sensor-Based Decision Making in Unstructured Environments

The reduction or transformation of sensor data into a form that can be used for control or decision making is a central problem in robotics. I view the problem of sensor-based decision making in terms of two components: a sensor fusion component that isolates a *set* of models consistent with observed data, and an evaluation component that uses this information and other task-related information to make model-based decisions. In this paper I describe a computational procedure for computing the *solution set* of parametric inequalities describing a sensor-object imaging relationship, and discuss the use of task-specific information to support set-based decision making. Experimental results indicate that this methodology is a promising and viable approach to the problem of decision making in unstructured environments.

Herbert SCHÜTTE

Analytical inverse transformation of the velocity and acceleration for a 6-dof robot and velocity optimization along a spatial spline trajectory

From measurements it can be seen that the controller error for a robot joint is almost two times smaller if one uses analytically calculated feedforwards in the control scheme instead of the feedforwards calculated by filters. This inside has led to the development of a formalism which makes it possible to calculate the feedforwards up to the second derivative in joint space from a corresponding description of the cartesian motion of the end effector, even for a manipulator withour central wrist. The consideration of a spatial spline trajectory and the optimization of the velocity along this path is shown together with corresponding results. The user interface of the open loop control for 6-dof robot and the integration of the whole software components of the control on a special transputer hardware ends the contribution.

Werner SCHIEHLEN

Mathematical Relation between Multibody Dynamics and Robot Dynamics

The general purpose formalisms for multibody systems have proven to be inefficient for applications in real time robot applications. On the other hand special algorithms have been developed for applications in robotics. It will be shown, that there exists a direct mathematical relation between multibody dynamics and robot dynamics. From this point of view the choice of coordinates, the dynamical principles used and the symbolical formula manipulation is most important for efficient dynamic robot computations.

Klaus SCHRÖER

Robot Calibration: Method, Results, Problems

For many applications, robots are needed which have an absolute cartesian pose accuracy the same order of magnitude as their repeatability. Calibration procedures have to be applied to reach this aim. A calibration procedure was presented which allows the automatic determination of all kinematic parameters, gear parameters, and static elasticity effects. It is based on a complete kinematic model which is combined with a gear model and an elasto-static deformation model. For parameter identification, an ordinary Gauss-Newton method combined with a line-search strategy is used. With the aid of this method it is possible to increase pose accuracy up to the robot's system limit as determined by its repeatability. Moreover, information can be acquired which gives hints toward improvements in robot design, thereby also improving repeatability. The problems of rank deficiency caused by prismatic joints and a possible aid from the field of differential geometry and of the necessity to model some of the model parameters as random variables and to identify also their variance are mentioned.

Inge TROCH

Time-(Sub)Optimal Continuous and Quasi-Continuous Path Planning

Frequently, point-to-point movements as well as continuous path movements are to be performed as quickly as possible. Modelling as a time-optimal control problem with control and state constraints is possible, but its practical solution requires not only special software tools but also involved mathematical investigations. Therefore, approximation as quasi-continuous movement is frequently performed and results in a polygon which has to be parametrized w. r. to time. First, improvements of Paul's algorithm are presented. Examples demonstrate that accuracy can be improved slightly whereas at the same time the overall movement time can be reduced considerably (down to less than 10 % of the time resulting from Paul's method) at the price of a moderate increase of computation time. Secondly, a sweep procedure is presented which yields the true time-optimal time-parametrization of a given path and which can be generalized to handle arbitrary constraints on the applied forces and torques and which yields the solution in such general cases after finitely many sweeps. Finally, the forementioned sweep method is applied to a simplified optimization problem where torque constraints are replaced by constraints on the accelerations. This allows the explicit computation of the optimal solution. Again, the efficiency of the proposed method is illustrated by an example.

Andrew GOLDENBERG

Decomposition of Spaces with Indefinite Inner Products and Their Application to Simultaneous Control of Force and Position

Using Screw Algebra, the proper inner product of wrenches & twists leads to indefinite products. Based on this product a decomposition into "orthogonal" spaces leads to four subspaces which under certain assumptions reduce to the standard orthogonal subspaces as used in Hybrid Control. The decomposition leads to very interesting interpretation of force and motion subspaces and their relative relationships in the overall motion/constraint space.

Herman BRUYNINCKX

Some Invariance Problems in Robotics

The careless application of linear algebra to a lot of robotics research fields has led to some misleading, because non-invariant, results. The most important source for this non-invariance is the unfamiliarity with the fact that no "natural", Euclidean-like norm exists for rigid body kinestatics. Other non-invariant theories described in this paper rely on the construction of physically nonsemical "operators", or on a non-invariant description of motion constraints. This paper explains where and in what form the problems appear, and presents possible solutions by introducing physically relevant operators. The existing non-invariant theories are (formally!) just special cases of the proposed solutions, by simply equating the newly introduced operators to the identity operator. However, the main difference between the non-invariant theory, and our solutions lies in the fact that the introduced operators obey transformation requirements.

Eduard REITHMEIER

Position and Force Control for Robot Manipulators Subject to Parameter Uncertainties

The increasing utilization of robot manipulators in industrial tasks such as assembling, handling of hazardous waste, folding, marking etc. depends greatly on available hybrid position and force control schemes. Since the robot as well as its environment are often subjected to uncertain imperfections such as Coulomb friction in the links, backlash in the gears, not exactly known masses and dimensions etc., it is necessary to design controllers which are robust with respect to these uncertainties. In addition, the dynamics of the robot are nonlinear, that is, nonlinear control aspects have to be taken into account. Another aspect to be taken into consideration is the relative stiffness of the robot, the force sensor and the manipulated surface. This fact requires some attention on the contact force model. We propose a control scheme which accounts for this point of view and demonstrate its efficiency with respect to robustness and accuracy of position and force tracking by means of numerical simulation and animation. The control design is based on the constructive use of Lyapunov functions.

Richard W. LONGMAN

Learning and Repetitive Control in Linear Systems

Learning and repetitive control is a new field that has developed motivated by the repetitive nature of robot operations on an assembly line. In a deterministic environment, when a control system is given a command to track a changing input command, it will produce the same tracking errors every time. Learning and repetitive control laws oberserve the error in following the command each repetition and adjusts the command from one repetition of the task to the next in order to improve performance. The aim is to converge upon the task command that will produce the desired tracking solution - i. e. the command is no longer the desired response, but instead is the command needed to produce the desired response. This paper gives an overview of learning control approaches developed by the author and his co-workers. These include methods based on integral control concepts applied in the repetition domain, based on direct model reference adaptive control, based on indirect adaptive control and based on numerical optimization methods. Methods are developed that guarantee convergence to zero tracking error, as well as ones which produce tracking in a least squares or quadratic cost sense. Decentralized learning control is also discussed.

Pierre DAUCHEZ

Some Experiments With a Two-Arm Robot (Video)

When two robotic arms manipulate a single object, some kind of force control is often necessary. We propose a hybrid position/force approach in which the position variables are the absolute trajectory of the object and the relative trajectory of the arms and the force variables are the external and internal forces acting on the object. Diagonal selection matrices are used for selecting the proper variables to be controlled, depending upon the task. We have implemented our method on a multiprocessor architecture to control two Puma's 560, equipped with two force sensors. The experiments presented in the video include:

- the manipulation of rigid objects firmly held, with andwithout control of external forces,
- the manipulation of three boxes non-firmly held with control of an internal force (external force control can also be added),
- the deformation of a spring by controlling its internal force,
- the assembly of two objects, with each being held by one arm, with control of the contact forces seen as internal forces. In this last case, the approach phase of the end effectors (before contact) is also presented. It involves a relative description of the task, i. e. the trajectory of one end effector is defined with respect to a mobile frame attached to the other end effector.

For all these experiments, no dynamic effects are taken into account and simple control laws are implemented. Some simulations have been undertaken to test more advanced control algorithms; these algorithms will be first tested on a three-degree-of-freedom parallel robot, which is also presented in the video, along with the future transputer-based controller we are now developing.

Edda EICH

Efficient Numerical Integration of DAEs for Mechanical Systems with Constraints and Invariants

Multibody dynamics with position constraints, contact problems, Coulomb friction or invariants lead to DAEs of index ≥ 2. Reducing the index by differentiation leads to instability and the numerical solution violates the constraints.

The lecture presents a quasi-orthogonal coordinate projection method, which can in principle be used with any discretization method. In numerical tests this yields much more accurate solutions, as can be easily seen by convergence analysis. The effort for computation of projection is minimized by monitor techniques. It is shown that the fastest method for generation and solution of equations of motion is a combination of a recursive formalism solving the inverse problem of Robotics and a monitor technique used to solve the linear systems iteratively. For the special case of linear multisteps new technique exploiting the structure of the equations and improving the efficiency of the method are discussed.

Numerical examples of practical problems in mechanical engineering are presented to illustrate the approach.

Marc STEINBACH

Efficient Parallel Algorithms for the Numerical Computation of Optimal Point-to-Point Trajectories of Robots

Numerical computation of optimal point-to-point robot trajectories can substantially increase the performance of assembly lines, and is also an important tool in optimal robot design. Different numerical algorithms based on multiple shooting are discussed, which have a high degree of parallelism. Indirect methods are hard-to-use and require much man-power because of usually complex solution structures (singular control arcs, inequality constraints). Therefore sophisticated direct methods are developed, which are based on an optimally taylored combination of multiple shooting and sequential quadratic programming techniques in connection with special high-rank update procedures. Numerical results demonstrate that such easy-to-use methods are very fast and sufficiently exact for routine industrial application.

Walter SCHENKER

Suboptimal Control of Mechanical Systems under Consideration of Symmetries and First Integrals

We treat the classical problem of optimizing a mechanical system given in Hamiltonian form

$\dot{x}_q = \partial H/\partial x_p, \quad \dot{x}_p = -\partial H/\partial x_q + Q(x_q, x_p, u)$ with respect to the performance index

$s = \int_{t_a}^{t_e} L(x_q, x_p, u)\,dt + K(x_q, x_p)$ instead of going the usual way of solving a boundary value problem with algebraic equation $\partial H/\partial u = 0$.

We raise the dimension to get the so called underlying Hamiltonian system

$\dot{x} = \partial H^g/\partial\lambda, \ \dot{\lambda} = -\partial H^g/\partial x, \ \dot{\rho} = -\partial H^g/\partial u, \quad \dot{u} = h(x, \lambda, u)$ with $H^g = L + \lambda^T f + \rho^T h$.

Optimal case: $\rho = \dot{\rho} = 0$.

The raised system "lives" on a manifold $E(x, \lambda, \rho, u)$ with symplectic 2-form

$w = d\lambda \wedge dx + d\rho \wedge du$. On this manifold we consider different sets of first integrals with (1) Liouville integrability, (2) integrability in the non-commutative sense. We although perform reduction of the system by symmetries.

Rhonda SLATTERY

Optimal Control of Closed Chain Robotic Systems

Two robot arms grasping a common payload form a closed chain system. The advantages of a two arm manipulator over a one arm manipulator are in moving large or awkward loads, and in increased stability due to two contact points on the payload. A disadvantage is the more complicated dynamics arising from the closed kinematic chain structure.

A method for deriving the equations of motion of a closed ring system is presented which is related to two arm force control. This method emphasizes the payload rather than one of the arms. The equations of motion are used to determine minimum time and fastest throw paths for a simple planar robot system. The actuators have bounded torques. The minimum time solution is generally bang-bang in all controls. There are more controls than degrees of freedom for this system, and the extra control authority leads to large internal forces in the payload. Problems with constraints on these forces are also examined.

R. W. LONGMAN, Volker SCHULZ

Space Based Robotics

This paper gives an overview of a series of papers by the authors, as well as discussion and computer demonstration of new results in robot trajectory generation in space.

Results are discussed concerning: 1. new kinetimatics for robots mounted on satellite with attitude control systems functioning in order to account satellite motion. 2. Reaction moment compensation to eliminate attitude disturbance from the robot. 3. New forward and inverse kinetics problems that take the place of forward and inverse Kinematics problems when the attitude control system is turned off. 4. The robot work space for space based robotics. 5. The effect of flexibility. New results are given stating from a mathematical formulation, and interpretation based on the group SO(3) at computer animation of numerical solutions that are feasible solutions to maneuver the robot without a net rotation of the spacecraft at the end of operation.

P. S. KRISHNAPRASAD

Nonholonomic Geometry, Mechanical Systems and Optimal Control

Precise nonlinear dynamic models have had a significant role in the analysis, simulation and control of a variety of mechanical systems. The use of global geometric methods, including concepts based on symplectic geometry, symmetry groups and reduction, leads to valuable insight into the qualitative properties of such models. In the formulation of (constrained) motion planning problems for space-based robots, a very powerful tool is derived from the theory of geometric phases. It is noteworthy that geometric phases have recently been the subject of intense study in a variety of areas of classical and quantum physics. In this talk, we will indicate the common mathematical framework underlying such applications in physics and our work in robotics. We will indicate some recent developments in the growing field of nonholonomic geometry that have a direct bearing on questions of interest to control.

Nonholonomic geometry is concerned with those aspects of geometry that are natural consequences of constraints and symmetries. Related variational problems can be motivated by optimal control (of driftless systems) and singular riemannian geometry, and vakonomic mechanics. Some problems of efficient manipulation can be easily cast into this form. One can identify various explicitly solvable cases of such optimal control problems using the underlying geometry. Here elliptic functions play an important role. In this talk we will show how symplectic and poisson reduction methods play an important role in identifying explicitly solvable problems.

Clementina D. MLADENOVA

Mathematical Methods in Modelling and Control of Manipulator Systems: Group Theoretical Approaches to Analysis and Control

The investigations under consideration present a uniform approach to modelling and control of manipulator systems based on Lie group theory for rigid body and rigid body systems description. The partial isomorphism between the orthogonal transformations group and the group of vectors with a definite composition law (existing only in the three-dimensional space), brought to the idea of using the so called vector-parameter for manipulator systems describing.

The group essence of manipulator configurational space introduces a new sense in the theoretical considerations. The kinematics and dynamics of the open-loop mechanical systems are presented by algebraic and differential equations over a group manifold.

The vector-parametrization of the rotation group SO(3) is chosen because of the fact that its simple composition law gives the possibility the basic requirements to real-time control - minimum calculation operations to be satisfied.

Rainer HETTICH

Semi-infinite programming methods in robotics

Recently, for the optimal path tracking problem an approach has been suggested [Marin '88], which transforms this problem into an optimization problem the constraints of which bound the ranges of some functions in their whole domain. Problems of this type are denoted as Semi-Infinite-Programming (SIP) problems. For the path tracking problem results will be presented, which indicate that in comparison for instance with dynamical programming methods the SIP approach seems to be efficient, accurate and very flexible w. r. t. the robot model and various constraints. Possible further applications of SIP in robotics will be indicated.

Peter C. MÜLLER

Collision Avoidance of Robots

A survey is presented on different types of problems and algorithms for the collision avoidance of robots related to fixed or moving obstacles within the robot working cell. Different aspects are dealt with: detection of obstacles, collision-free path planning, and control algorithms avoiding collisions. Certain algorithms of the literature as well as one new algorithm are discussed and compared.

Friedrich PFEIFFER

Manipulation processes of elastic robots, nonlinear dynamics (impulsive and stick-slip-processes)

Considering manipulators with elastic links and joints includes some additional mathematical efforts in modelling dynamics and control of such systems. Existing path planning methods for rigid robots must be extended by taking into account elasticity, similarly control concepts have to be modified. An elastic robot affords the application of elastic multibody-theory, which again involves additional mathematical problems. All methods necessary to solve the relevant problems will be presented and applied to a laboratory robot, which at the same time is used to verify theory.

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