MATHEMATISCHES FORSCHUNGSINSTITUT OBERWOLFACH

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Kinematik und Robotik

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The conference has been organized by Hans Georg Bock (Heidelberg), Manfred Hiller (Duisburg), Josef Hoschek (Darmstadt) and Friedrich Pfeiffer (München). A total of 41 researchers (mathematicians and engineers) from 13 countries participated, and 37 papers were presented. Some of the fields treated are the following:

1. Theoretical kinematics
2. Screw theory
3. Spatial motions
4. Parallel manipulators
5. Symbolic processing
6. Nonholonomic systems
7. Spatial contact kinematics
8. Robot and manipulator design
9. Workspace analysis
10. Motion control of robots, manipulators and platforms

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11. Task and path planning for robots

The conference has been organized in this form for the first time, combining a preceding series of kinematics and robotics conferences, respectively. The aim was to bring together the researchers working in the theoretical field with those working in practical applications. Lively discussions after the talks, during the breaks and meals as well as in the evening in the pleasant environment of Oberwolfach showed that this concept went down very well. Everybody agreed that this conference should be repeated soon in the future.

ABSTRACTS

J. ANGELES:

Kinematics of Manipulators with Parallelism, Modularity and Redundancy

Most of industrial robots are supplied with a serial architecture, which brings about serious drawbacks, such as low load-carrying capacity, narrow bandwidth, and high joint and link flexibility. To cope with these drawbacks, parallel manipulators have been proposed, but these solve the foregoing problems only at the expense of workspace volume and dexterity. As a means to overcome the foregoing shortcomings of parallel manipulators, we propose here the use of modular architectures supplied with redundancy. In this way, manipulator dexterity and workspace volume are enhanced, while the structural robustness of parallel manipulators is preserved.

S. ARIMOTO:

Nonlinear Position–Dependent Circuits Expressing Robotic Motions Under Constraints

A class of nonlinear position dependent circuits is introduced, which express dynamics of mechanical systems such as robot arms and mechanical hands under geometrical constraints. Such a circuit consists of subcircuits which are linked to each other through a Jacobian matrix between one position coordinate and another position coordinate. It is shown that the linking condition can be derived naturally from the principle of virtual work or Hamilton's principle. Due to the passivity property of such nonlinear circuits it is possible to design a simple feedback control scheme for setpoint position control and show its asymptotic stability of positioning under geometric constraints. Further, it is shown that a deep insight into physical interactions between robots and their task environments can be gained via the analysis of such nonlinear position-dependent circuits, which may give rise to physical understanding of dexterous robot motions.

F.L. CHERNOUSKO:

Simulation and Optimization of Regular Gaits of the Tube–Crawling Robot

The tube-crawling robot designed by Prof. F. Pfeiffer in Munich Technical University has eight two-linked legs attached to the central body and can walk inside tubes using a wide variety of possible gaits. We confine ourselves to the regular gaits for which the speed of the central body in the cylindrical tube is constant, and all legs move in a similar way. To determine the torques created by the motors in the robot joints, we calculate the reaction forces (normal and friction forces) acting on the feet of the robot. After that, the regular gaits of the robot are simulated. The results of computer simulation show that the robot walking characteristics (speed and driving force) are rather sensitive to the variation of the gait and structural parameters. Hence, optimization of the robot characteristics with respect to these parameters seems reasonable. Some results of the optimization are presented and discussed. The paper is based on the joint work with N.N. Bolotnik and G.V. Kostin.

D. CHEVALLIER:

Coordinate Free Criteria for Testing the Linear Dependence of Sets of Screws

The verification of the linear dependence and the calculation of the rank of a set of screws are very important tasks in kinematics in the search for singular positions of open chains as well as in the search for movability conditions of closed loop chains. This mathematical problem is generally solved by standard techniques of linear algebra using determinants of coordinates of the screws relative to more or less arbitrary bases. However, such methods make no use at all of the specific algebraic structure which can be defined on the set of screws and, as for any coordinate method, the geometrical meaning of the result may be unclear.
It is well known that the checking of the linear dependence of a set of ordinary vectors in three dimensional space can be completely performed by use of coordinate free criteria relying on the properties of the vector product and the triple vector product. Nevertheless, to our knowledge, no similar coordinate free criterion has been exposed in screw theory. In this paper we expose a list of mathematical properties leading to an algorithm for testing the linear dependence or computing the rank of any set of screws. In some sense, this list generalizes to the Lie algebra D of the displacement group the two classical criteria valid in ordinary

vector algebra (the Lie algebra of the rotation group). Due to the higher dimension of the vector space, many particular cases must be studied for the design of a complete algorithm. They are the concern of specific criteria and so the finite sets of screws are divided into three classes including respectively three, four and eight non trivial subcases.

Several remarks seem to be noteworthy. First, the expressions for these criteria require all the algebraic operations defined in an earlier paper by Chevallier, in particular the Lie bracket and the module structure of D derived from operation V, except operation III. In other words the classical form of screw theory using only the vector space structure and the Klein form should not contain all the necessary tools for this. This echos a statement of Hervé: the mathematical properties of the displacement group and its Lie algebra are a key to the understanding of kinematics.

Second, the form of the general criteria seems to be closely related to properties met in the kinematics of overconstrained mechanisms, such as the existence of transversals; the following results contain a purely algebraic technique for pointing out such "transversal screws" in various cases. The eight criteria exposed for the third correspond to simpler applications and one can find corresponding mechanisms with finite or infinitely small mobility.

Third, the classification of vector subspaces of D (screw systems), has been recently studied by Rico Martinez and Duffy and by Gibson and Hunt. Here we consider a given set of generators, in practice the data defining a linkage in some configuration, and we solve a rather different problem.

E.A. DIJKSMAN:

Four-Bar Branch Cognates of Eccentric Inverted Slider–Cranks: "Is it Possible to Elude Roberts' Law?"

Recently, the degeneration of Roberts' Law was amended for inverted slider-cranks producing symmetrical curves. Then, a very good approximation was obtained based on *stretch-rotation* and *symmetrization*. However, for the *eccentric* type, symmetrization is not applicable and has to be replaced by a more general procedure, based on *three* accuracy positions of a (transformed) bar interconnecting points of a new crank-circle with the corresponding accuracy points of the initial curve that is produced by an arbitrary coupler point of the eccentric inverted slider-crank.

For the *two* Grashof-types, each coupler-branch of the inverted slider-crank, will be reproduced by a slightly different four-bar. For each of the *two* Non-Grashof-types, only a singular curve appears of which each time not more than *half* the curve is reproduced. Then, both, the eccentric inverted slider-crank as well as its corresponding 4-bar curve cognate are Non-Grashof simultaneously.

The way to derive these approximated 4-bar branch cognates will be explained in more detail.

J. GRILL:

Calculation and Optimization of Grinding Wheels for Manufacturing Grounded Gear Hobs

A new method has been developed which allows to calculate the grinding wheels profile for manufacturing grounded hobs. High accurate gear hobs, for hobbing spur and helical gears, cylindrical worms and worm wheels, will be manufactured on cutter grinding machines. Thus, the manufacturers of hobs have to determine the grinding wheels profile out of the profile of the hob and further data like the lead angle, the relief and the rakeangle or the diameter of the grinding wheels.
There are no explicit functions for calculating the grinding wheel's profile and thus an iterative method has been developed. The cutting edge of a hob is the intersection of a grounded flute and a relief grounded flank. The flute and the flank are conjugated surfaces of grinding wheels. The coordinates, the first derivatives and the first and second fundamental forms of conjugated surfaces can be calculated by using a general method, which allows to determine the fundamental forms of a generated surface out of the fundamental forms of a generating surface.
By using this method and the formula of Meusnier, the cutting edge profile with its first derivative and its curvatures, the fundamental forms of the enveloped helicoid and the standard basic rack tooth profile with its first derivative and its curvatures can be calculated. Finally, by a variance comparison of the actual and the desired standard rack tooth profile of the grounded hob, the profile of the grinding wheel can be optimized.
The results of the iteration are the profiles of the grinding wheels, the cutting edges, the faces of the cutting teeth, the relief grounded flanks with their first derivatives and their curvatures and an optimized regrind-table for minimizing the deviations of regrinded hobs.

J. HERVÉ:

A Family of Overconstrained Linkages via the Displacement Sub–Group of Dimension 4

The set of all possible Schoenflies motions makes up the dimension 4 sub-group $\{X(\mathbf{u})\}$ of the Euclidean displacement group. Two in parallel X mechanical connections between two rigid bodies realize a single loop kinematic chain.
The total number of freedom is $4 + 4 = 8$.
The Tchebychev mobility criterion predicts a degree of freedom 2 for the resulting chain.

In fact, the intersection set of two X sub-groups (with distinct direction unit vectors $u = u$) is the 3 dimensional sub-group of spatial translations $\{T\}$ and the kinematic chain has the mobility 3. Such a type of exceptional mobility is useful for the design of new manipulator robots (Delta, Star, H, Prism ...). Locking one degree of freedom in each X generator generates a closed loop with the degree of mobility 1. One may recognize the Koenig homokinetic joint and new mechanisms with one degree of freedom.

T. HORSCH:

Spline Interpolation for Industrial Robots and its Applications

At the time being, mainly two elementary Cartesian interpolation methods are existing for commercial industrial robots: linear and circular interpolation.
Each robot movement is composed of these elementary movements with possible speed discontinuities. In the near future, total movements more and more will be available as CAD data, generally, however, without orientation information.
Right now, Reis examine methods for interpolation with NURBS. Doing so, on the one hand great importance is attached to suitable interfaces for integration of CAD data (as far as possible) and for facilitated programming of complex parts in teach-in method on the other hand. This may considerably reduce costs.
The presentation is composed of two parts. The first part explains the problems and gives proposals for solution. The second part shows existing applications and those possible with this new technique in the future.

M. HUSTY:

Parallel Manipulators: Direct Kinematics and Singularities

Singularities of parallel manipulators have been studied in detail by several authors. A special kind of these singularities are the continuous ones. A parallel manipulator which is in such a singularity gains one or more degrees of freedom while all actuators are locked. In this paper we introduce a part of the first systematic study of self-motions of parallel manipulators of the Stewart-Gough platform type. The study representation of the group of Euclidean congruences is used and additionally the image space representation of the condition that a point of the moving system is constrained to move on a sphere. We believe that a case study like this has to precede any direct kinematic analysis of parallel manipulators.

B. JÜTTLER:

Spatial Rational Motions

Using spatial rational motions it is possible to apply the powerful methods of Computer Aided Geometric Design (especially the Bézier– and B–spline techniques) to problems from kinematics, robotics and animation. These motions are defined by the property that the trajectories of all points of the moving object are rational curves.

We present a construction for rational motions of fixed degree and outline some algorithms for interpolation and approximation of a sequence of positions of a moving object. Moreover we discuss several control structions for rational motions which are analogous to the control polygons of B–spline curves. Based on the dual representation of a motion we are able to compute an exact representation of the boundary surface of the region which is traced out by a moving polyhedron. Finally we discuss rational sweeping surfaces.

This talk is based on a joint work with Michael Wagner (University of California, Davis).

A. KARGER

Singularity Analysis of Serial Robot Manipulators

This lecture is devoted to the description of the singular set of serial robot manipulators. For 6 degrees of freedom robot manipulators we have developed a theory which allows to discuss higher order singularities of serial robot manipulators. By using Lie algebra properties of the screw space we give an algorithm, which determines the degree of a singularity from the knowledge of the actual configuration of axes of the robot manipulator only. The local shape of the singular set in a neighborhood of a singular configuration can be determined as well. We also solve the problem of escapement from a singular configuration.

For serial robot manipulators with the number of degrees of freedom different from six we show that up to certain exceptions singular configurations are removable. It means that they can be avoided by a small change of the motion of the end-effector.

We also give an algorithm which allows to determine equations of the singular set for any serial robot manipulator. We discuss some special cases and give examples of the singular set including PUMA 560.

M. KAUSCHKE:

Using Closed Form Inverse Kinematics Solutions for Redundant Robot Configuration Planning

It has turned out that the closed form solution for the inverse kinematics problem (IKP) efficiently can exploit computational simplifications resulting from specialized kinematic structures of nonredundant serial link robots. In this talk a method for expanding the use of such solutions to redundant robots by combining symbolic and numeric means will be presented. The resulting method is well suited for low degrees of redundancy and not necessarily describable tasks. Some examples in the area of collision avoidance for a 8 DOF robot will be given.

A. KECSKEMÉTHY:

Automated Symbolic Processing of the Kinematics of Multiple-Loop Mechanisms

Described in this paper is an approach for the automatic generation of optimized symbolic expressions for the kinematics of multiple-loop mechanisms at position, velocity and acceleration level. The theoretical foundations of the approach are based on the concept of the kinematical transformers introduced in previous publications. The particular features of the implementation are: (1) recognition of closed-form solutions for decomposable subsystems; (2) automatic tracking of input-output dependencies; (3) automatic selection of secondary joints for efficient iterative solution of subsystems for which no closed-form solutions are found; (4) optimized selection of vector decomposition frames on a loop-by-loop basis for efficient velocity and acceleration analysis. The practical usefulness of the approach is illustrated by the application of our current Mathematica implementation to diverse robotic and automotive systems.

D.R. KERR:

A Finite Twist Representation and its Application to Workspace Analysis and Manipulator Design

A compact characterization is derived from the general screw transformation matrix, representing rigid body displacements. This representation of relative finite motion is applied to examples of manipulators and to examples of tasks. A means is described of characterizing the kinematic workspace of planar serial and planar parallel manipulators, and of extensions that offer the possibility of designing manipulators for prescribed families of tasks.
A indication is given of the means of applying the above also to spatial tasks and manipulators.

J. KIENER:

Dynamic Modelling of an Underwater Robotic System

Underwater Robotic Systems (URS) consist of a free–floating platform and at least one manipulator, which is mounted on this platform. Usually, these systems have twelve or more degrees of freedom. The derivation of the dynamic model of such a system poses the difficult problem of dynamic coupling between platform and manipulator. Moreover, planning trajectories and deriving a control scheme requires solving a redundancy problem.
In this lecture, first, the system dynamics of an URS are presented, including the most important hydrodynamic effects (Added Mass, drag) as well as the hydrostatic influences (buoyancy, fluid acceleration). Then, the O(n)–algorithm, which is used for forward dynamics simulation, is introduced. Due to the mobile base and to the hydrodynamic effects, the standard formulation of this algorithm has to be modified when used for URS. Simulation results obtained with a simulation program which uses the modified O(n)–algorith are shown. As far as control of an URS is concerned, the basic concepts for designing a control system are presented. Some results from PID–control of the platform alone are also added.

P. KOVACS:

New Algebraic Strategies for Open Problems in Kinematics Analysis

The lecture gives a survey of a chain of interconnected new concepts in algebraic elimination and their application to kinematics analysis. The methods are illustrated by two previously unsolved problems.
First, a parametrized symbolic solution of the VW R30 manipulator, which is an 8th degree open kinematic chain, is derived. In practice, this solution can neither be obtained with the advanced Lee-Liang/Raghavan Roth Algorithm nor with elaborate ideal-theoretic methods like the Buchberger Algorithm or multivariate resultants. The new methods show that theoretically, the above algorithms would provide a standard representation of some optimal univariate characteristic equation of the VW R30 which consists of 3580 complex terms. If it were obtainable, it would be practically impossible to simplify this representation. The presented methods are able to provide a parametrized symbolic solution and yield a representation of the crucial univariate equation as a sum of three simple products, requiring 41 multiplications for its evaluation instead of the thousands of multiplications required in standard form.
As a second example, a simple, parametrized symbolic solution of the kinematic structure of the cycloheptane molecule is derived. This was a long open problem in theoretical chemistry (conformational analysis). All six univariate equations are of degree 16 in this case and have very complex coefficients which are high degree polynomials in the parameters (one input joint and one structural constant).

We prove that none of the six permits some essential standard simplification like factorization, functional decomposition or bivariate homogeneous decomposition. In contrast, the presented symbolic solution of cycloheptane consists of a sequence of some very compact eight degree polynomial and a simple quadratic polynomial that yield all sixteen solutions for one of the variables. The equations for the remaining variables are linear.
The approach is based on a new concept in algebraic elimination which is called functional ideal decomposition and on a generalization thereof. If applicable, the methods simplify the elimination process of arbitrary polynomial systems significantly. The relationship between functional ideal decomposition and functional decomposition of single polynomials is similar to the relationship between ideal factorization (primary decomposition) and factorization of single polynomials. From a certain perspective, the approach can be seen as an attempt to generalize invariant theory.

H. LI:

Video: Development and Application of the TELBOT System

This paper presents an overview of the TELBOT system - a new tele robotic system, including the development, design, kinematics, calibration, path planning, control, simulation and applications. The TELBOT system consists of a 6 DOF manipulator with 6 revolution joints, a control system and a simulation system. All the motors, measuring system and the transmission gear box of the manipulator are located in the robot base. There are no cables from the base to the end-effector. The transmission of the motion from motors to the end-effector is realized via concentric tubes and bevel gears. All the revolution joints can be rotated over 360 degrees. Because of the off-set at the 5th joint, there is no closed-form solution of the inverse kinematics. The method to solve the inverse kinematics problem of series-chain manipulators with general geometry proposed in the earlier papers of the author is used to find all the 16 possible configurations. It greatly facilitates selecting the optimal configuration for a given workspace and avoiding obstacles. The end-effector can reach any position in any orientation in its workspace. The control system is designed as an open system, the hardware is the VME bus system and the software is based on the VxWorks real-time operating system. A 3–D simulation system is connected to the control system for real-time visualization and off-line simulation. The complete robotic system has been applied for nuclear steam generator maintenance, and exhibited many times in Germany, France and Japan.

R.W. LONGMAN:

Recent Progress in Learning Control for Precision Robot Tracking

The output of typical control systems is a convolution of the command, and not equal to the command given to the system. In many applications, such as robots operating on an assembly line, control systems are given the same command repeatedly, and in such cases the control system repeatedly makes the same errors. Learning control is a relatively new field that develops controllers that learn from previous experience performing a specific command in order to improve future performance with that command. The simplest form of learning control is based on using integral control concepts applied at each time step and "integrating" in repetitions. This control law is guaranteed to produce zero tracking error under very general conditions, which are nearly independent of the dynamics of the system. However, in practice, it is common to encounter error transients during the learning process that are unacceptably large. Hence, there is a need for learning algorithms that learn with good transients. Two versions are discussed here: ones producing monotonic convergence of the error norm with repetition, and ones that have monotonic convergence of the steady state frequency response components. The range of learning control laws that have been developed is discussed, together with methods of obtaining robustness of the good transient behavior to uncertainties in the system model. Experimental results are shown for many learning control laws applied on a seven degree-of-freedom Robotics Research Corporation robot. The best of these algorithms decreases the rms tracking error of the robot by a factor of 1000 in 6 repetitions of the task. Other experimental results are shown using such algorithms to eliminate velocity errors in a precision timing belt drive system, where the errors are repeating due to geometric inaccuracies in machining of parts and in tooth meshing. The demonstrated ability to greatly improve the tracking accuracy of mechanical systems, means that learning control has many important industrial applications.

K. MARTI:

Stochastic Path Planning for Robots

In order to reduce large on-line measurement and correction expenses, the a priori information (given by certain moments or parameters of a probability distribution) on the random variations $p = p(\omega)$ of the vector p of model parameters are taken into account already in the planning phase. Thus, instead of solving a deterministic path planning problem with fixed estimated data, here, the optimal velocity profile $\beta(s) = \dot{s}^2(s)$ along the given trajectory $\underline{x}_e = \underline{x}_e(s)$, $0 \leq s \leq s_e$, is determined by using a stochastic programming approach. Consequently, the Polygon $V(s,p)$ of Constrained Motion is replaced by a more general Set $V(s)$ of Admissible Motion, determined by change constraints or more general expected cost constraints. The properties of $V(s)$ are considered for several probability distributions of $p(w)$. Moreover, the solution of the stochastic minimum-time path planning problem is compared with the solution of the standard optimal deterministic trajectory planning problem.

T. MEITINGER:

Spatial Contact Kinematics of Assembly Processes

The basic example for robotic manipulation is the peg–in–hole problem, where the dynamics of the robot are coupled with the contact mechanics between the mating parts. Up to now investigations in this area concentrate on planar models with a simple shape of the parts.
In the talk a spatial model of assembly processes will be presented. The manipulator is described by ordinary differential equations. Taking every contact point between the workpieces into account as an additional geometrical constraint, we obtain a system of differential algebraic equations (DAE).
For mating parts, which can consist of cylinders, cones, spheres and toruses, it will be shown how to describe the contact kinematics and the geometrical constraints. The later are formulated on acceleration level in order to include them into numerical simulation. Thus we can investigate the robots dynamic behaviour during the insertion task as well as the strains on the mating parts.

K.-H. MODLER:

Bagger als Roboter (in German)

Roboter üblicher Bauweise werden elektromechanisch angetrieben. Wegen ihrer geringen Leistungsfähigkeit (Kraft) sind sie für den Einsatz in der Bauindustrie nicht geeignet. Die neuesten Entwicklungen insbesondere aus Japan zeigen, daß in der Bauindustrie zukünftig hochflexible Handhabungssysteme eingesetzt werden müssen. Diese Robotersysteme können wegen der notwendigen hohen Leistungsfähigkeit sinnvoll nur mit hydraulischen Antrieben ausgeführt werden.
Im Vortrag wird ein elektrohydraulischer Stellantrieb vorgestellt, der gekoppelt mit einem Mikroprozessorsystem (MPS) das Führen offener Mechanismenketten auf vorgegebenen Bewegungsbahnen ermöglicht. Bei der Programmierung des MPS kann auf das Prinzip der direkten Auslegerwinkelzuordnung zurückgegriffen werden.
Mit dem Ziel, den elektrohydraulischen Stellantrieb zu realisieren, ist nicht nur die Suche nach praktischen Resultaten verbunden. Vielmehr stehen auch die theoretischen Zusammenhänge, besonders bei der Auslegung des hydraulischen Lageregelkreises, im Vordergrund. Dabei soll auch die enge Verknüpfung zwischen Hydraulik und Elektronik transparent gemacht werden.

Entsprechend dieser Zielsetzung werden zunächst die Grundlagen für das Verständnis des elektrohydraulischen Regelkreises mit seinen einzelnen Komponenten dargelegt. Anschließend sollen die allgemeinen mathematischen Zusammenhänge einer der insgesamt drei eingesetzten Regelkreise beschrieben werden.

A. MORECKI:

Modelling and Design of Elastic Manipulators, Walking Machine and Microwalking Robot

The talk is divided into three parts. The first part presents the latest results obtained during modelling (structure and kinematics) and design of two different kinds of elastic manipulators, namely an Elephant Trunk Type and a Spine Type Manipulator.
The second part presents a method of gait modelling-creation of the model (template) of motion - for a quadruped walking machine with the construction of its legs imitating the legs of digitigrade mammals (horse, rabbit). Some kinematical problems of old Chinese walking machine are presented.
The third part presents the class of walking microrobots. Fourlegged microwalking machine driven by Electromagnetic Force design and tested by the team of Robotics and Biomechanics of Engineering headed by A. Morecki will be presented.

P.C. MÜLLER:

Robot Control: Interaction of Modelling and Control Design

For the design of very accurate control of robots, complex models have been derived considering varying moments of inertia, couplings between the robot axes, effects of Coulomb friction within the joints, etc. Is this really necessary? In this contribution it is shown that the required quality of the mathematical model depends essentially on the method of control design. While the "method of nonlinear decoupling and exact linearization by state feedback" needs the knowledge of very accurate models, other methods such as the "method of nonlinearity estimation and compensation" does not require the same high quality of the model. Nevertheless it shows the same or even better accuracy of the control in practical applications. Presenting this second method a robust, very accurate, independent joint control of robots is developed based on a low level model. It is an example where the control design method essentially determines the required quality of the model.

B. RAVANI:

Computational Design of Smooth Spline Motions

This lecture deals with computational design of spline motions satisfying certain degree of smoothness. First, a generalization of Bezier curves to Riemannian manifolds is presented. Then, since a motion is a continuos path on a smooth manifold defined by its underlying Lie group structure, an algorithm is presented for design of motion splines. The algorithm is based on a de Castljau's type construction using the minimal geodesics derived by a special exponential map. The resulting algorithm is shown to be coordinate independent for interpolating rotations.
The rotation interpolation scheme is also extended to design of C^2 curves on $SO(3)$ satisfying a smoothness functional. On $SO(3)$, the smoothness functional with respect to the bi-invariant metric is chosen to be the integral of the squared Euclidean norm of the angular acceleration. It is shown using an appropriate approximation, that this results in a cubic spline motion as the solution of the two point variational boundary value problem. Examples illustrating the results are presented.

W. RISSE:

Sensor-Based Control of a Redundant SCARA-Robot

A redundant SCARA robot for operation in unstructured work spaces is presented that is equipped with distance sensors for both obstacle detection and end-effector guidance. Sensor-based Cartesian motion is generated to perform tracking of unknown surfaces with respect to distance and orientation. The inverse kinematics is based on resolved motion rate control utilizing the null-space of the robot's Jacobian for joint limit avoidance, repeatable motion in joint space and collision avoidance as secondary goals. The behaviour of the sensor-guided system is investigated within an integrated simulation environment and some typical results are presented.

O. RÖSCHEL:

New Results on Moveable Polyhedra

It is shown how to construct overconstrained mechanisms with systems linked by spherical 2R-links. Given a tetrahedron with faces tangent to a common sphere we cut the vertices of this polyhedron with planes tangent to that sphere. In the faces of this new polyhedron we define plane equiform Euclidean motions with global fixed points, straight line paths, common parametrization and common scaling factor $f(t)$. The motions in different faces are linked by spherical links.

"Blowing up" the tetrahedron with factor $1/f(t)$ then gives an overconstrained kinematic chain consisting of 8 systems linked by 12 spherical 2R-links. It has to be remarked that this procedure may be used to gain a very great variety of overconstrained mechanisms: The given algorithm just has to be applied to other polyhedra with faces tangent to a sphere. Some examples are discussed.

H. SACHS:

A Numerical Approach to Four-Bar Linkages in Minkowski-Plane

A Minkowski-plane M_2 is a real affine plane with an underlying vector space provided with the Lorentzian inner product $<\mathbf{x},\mathbf{y}>= x_1y_1 - x_2y_2$ for $\mathbf{x} = (x_1,x_2)$, $\mathbf{y} = (y_1,y_2)$. At first we show, that in M_2 exist exactly 72 different types of four-bar linkages with regard to the fundamental group B_3 in M_2, then we give a numerical method for calculating the four-bar linkage of type I(main-type), considering properties of first and second order (limit points, velocities, accelerations, asymptotes of the centrodes, rotation pole M, acceleration-pole G, inflexion circle, inflexion pole W, etc.) Above all we deduce some remarkable metric properties for the poles M, G and W.

J.C. SAMIN:

Full Symbolic Formulation of the Dynamics of Multibody Systems with Elastic Beams

The modelling of flexible elements in mechanical systems has been investigated through several methods issued from both the field of multibody dynamics and the area of structural mechanics and vibrations theories. As regards the multibody approach, recursive formulations in relative coordinates have been widely claimed to be really suitable and efficient for a large variety of applications. Such a formalism is developed here for a general multibody system containing flexible beams and in such a way that its full symbolic generation is possible within the ROBOTRAN program. Several validation examples are presented to illustrate the method.

D.J. SANGER:

Task Planning for Redundant Manipulators

The talk will outline a project which has employed an elastic model to resolve the redundancy in kinematically redundant manipulators. This has allowed the development of inverse position and inverse stiffness analyses, together with an extended inverse rate analysis. The consistency of the results of these analyses has provided the basis of a task planning method for redundant manipulators, which makes it possible for the manipulator to fulfill secondary tasks, such as obstacle and singularity avoidance, in addition to its primary task of positioning the end-effector in a defined manner.

W. SCHIEHLEN:

Synthesis of Multibody Systems by a Control Engineering Approach

The synthesis of multibody systems results in chain and/or loop topology. It is shown that the assembling of multibody systems may be represented as a transfer of flexible constraints into rigid constraints by a limiting procedure. It turns out that the controllability of multibody systems is not restricted to motions but it includes reactions, too. The number of input and output variables is not changed during the assembling. An example from robotics results in a combined motion and force control that is useful in many manufacturing processes.

M. SCHNEIDER:

Nonlinear Motion Control of Hydraulically Driven Large Redundant Manipulators

Hydraulically driven large-scale manipulators are complex mechatronic systems with highly nonlinear dynamic behaviour. For an easier understanding of this behaviour and as a basis of a nonlinear position control concept a nonlinear dynamic simulation model is required. It takes into account all relevant coupling effects between hydraulic drives and arm elements. The control tasks for the investigated manipulators are tracking prescribed trajectories and avoiding collisions with obstacles in the three-dimensional workspace. The most important problems one has to deal with are the complexity of the system, the nonlinear friction and elasticity of the hydraulic drives and the redundant structure of the arm package. Two different concepts for controlling the hydraulic actuators will be presented, both using the method of exact input-output-linearization.

J. SCHÖNHERR:

Kriterien der Übertragungsgüte für die Auslegung von Mechanismen, speziell von Parallelmanipulatoren (in German)

Der aus der Getriebesynthese bekannte Übertragungswinkel kann als einfaches geometrisches Kriterium für die Bestimmung der Abmessungen eines Mechanismus mit guten Übertragungseigenschaften genutzt werden. Daneben lassen sich mit Hilfe der Elemente der Jacobimatrix eines Mechanismus mit mehreren

Antrieben Ungleichungen zur Eingrenzung des Antriebsraumes eines Manipulators, ausgehend von maximal erreichbaren Antriebsgeschwindigkeiten oder -kräften angeben.
Umgekehrt dienen entsprechende Zielfunktionen, die auf die Minimierung der Antriebskräfte oder -geschwindigkeiten gerichtet sind, dem Auffinden optimaler Abmessungen des Mechanismus.
Die entwickelten Auslegungskriterien werden für die Bestimmung geeigneter Abmessungen ebener und räumlicher symmetrischer Parallelmanipulatoren mit 3 Antrieben verwendet. Dazu werden der Übertragungswinkel sowie aus geeigneten Gleichungen für die Rückwärtskinematik die Elemente der Jacobimatrix berechnet. Die Ergebnisse sind in Kurventafeln zusammengefaßt, aus denen sich die Kennwerte der Übertragungsgüte bzw. die für die Optimierung dieser Kennwerte notwendigen Abmessungen ablesen lassen.

H. STACHEL:

Instantaneous Spatial Kinematics and the Invariants of the Axodes

A remark in the Book BOTTEMA, ROTH: Theoretical Kinematics (page 161) says: *"The relationships between the local properties of the axodes and the higher order instantaneous invariants do not seem to have been developed."* This paper is intended to close this gap as well as to demonstrate again the elegance and the effectiveness that the use of dual line coordinates and dual quaternions brings about in spatial kinematics.
At the beginning the motion of the FRENET frame of a ruled surface is studied. Then we define the spatial motion Σ_1/Σ_0 by the FRENET motions Σ_2/Σ_0 and Σ_2/Σ_1 along its axodes. This gives new formulas for the instantaneous invariants of the spatial motion. (Some of these formulas have also been found 1973 at a seminar of H. VOGLER at TU Graz.) The paper ends with a short proof of DISTELI's formula and with the spatial analogon of the center-point curve.

M. STEINBACH:

Dynamic Robot Modeling and Trajectory Optimization

The lecture reports on a project aiming at the development of mathematical software for off-line programming and trajectory optimization in a CAD environment. Two typical application problems are presented, and consequences of problem structure and practical requirements on dynamic robot models and numerical solution methods are discussed.
The main part of the talk proposes a robust and efficient direct SQP approach for off-line trajectory optimization which is based on a structured interior point QP solver. First computational results for the new QP solver demonstrate its

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efficiency, especially for fine discretizations.

H. VOGLER:

Affined Darboux–Motions

About 1880 G. Darboux and A. Mannheim discovered motions in Euclidean three–space E_3 that move all points in planes which are not parallel. This lecture deals with motions in n–dimensional real affine space A_n with the property that all points have planar orbits. In 1985 A. Karger studied these Darboux–motions and gave a complete classification. He mostly was interested in the motion as submanifold of the corresponding LIE–group.
My approach is concentrated on the trajectories and an explicit representation of the motion. The investigations are based on the affine version of a theorem of A. Schoenflies and A. Mannheim – firstly discovered in the seventies of the last century and dealing with Euclidean motions that move every point of a straight line $g \subset E_3$ in a plane. The affine case which is in fact a projective one, was solved by the author. He found out that there are three cases as to the fact whether all planes of the trajectories are parallel to each other or only to one direction or have general position. The last type leads to trajectories that are affine equivalent with respect to the parameters of the motion.
This is the fundament for a total survey for Darboux–motions in A_n. The planes of the trajectories are parallel to each other (1st case) or parallel to only one direction (2nd case) or the trajectories are mutually affine equivalent with respect to the parameters of the motion (3rd case) or all planes intersect a certain plane at infinity (4th case). Explicit parameter representation in all cases are given.

C. WOERNLE:

Nonlinear Motion Control of a Nonholonomic Mobile Platform by Exact Linearization

For a nonholonomic mobile platform with two independently driven wheels and a passive third wheel, a path following control problem is formulated. The distance of a platform-fixed reference point located on the wheel axis in combination with the forward velocity of the vehicle are made to follow prescribed time functions. The reference point tracks a path given as an algebraic curve with desired speed. The wheel axis is always orthogonal to the path. The control law is obtained by exact input-output-linearization via dynamic state feedback, whereby differential-geometric characteristics of the path up to the third order are used.

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