of cleaning and inspection. Difficulties were only encountered in the starting phase, in which the position of the robot relative to the pipe node and the tool changing system did not properly match the values calculated by the CAD-system. After adaption of the CAD-system, the simulated robot manoeuvres could be duplicated in the predicted manner at the real pipe node. Special care was taken to ensure the proper monitoring of the end effector motions along the welding seam of the pipe node. Parameters, such as the working area, process specific tool motion, tool distance and tool orientation were considered.

The verification of the offshore-relevant cleaning and inspection was a success, which demonstrated the potential use of the installed software system.

6. Concluding Remarks

An off-line programming and simulation system for an automated underwater handling system was presented. It is designed as a programming aid for the submersible and the robot, and as a graphical simulation system for mission planning.

The work with the off-line programming and simulation system of the OSIRIS-project has shown that it is necessary to use this kind of system for the planning of underwater handling tasks. Moreover, it is necessary to execute the simulated tasks at the real test site to verify if the system is able to perform the job in a full, real environment. Future work will be focused on the elaboration of the developments mentioned above and the installation of the test site within the pool of the GKSS-Underwater-Simulator GUSI, where necessary practical tests and program verifications can be performed under real underwater conditions.

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Robot Obstacle Avoidance Using Vortex Fields

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Abstract

A new method is presented for planning collision-free robot motions in the presence of workspace obstacles, based on the use of artificial potential fields. In previous approaches, obstacles are modeled by means of repulsive potentials, which give rise to local minima in the total field, possibly causing the planning algorithm to jam up. Instead, the core of the proposed technique is to place vortex fields around obstacles, forcing the robot to turn around them and preventing the generation of local minima. In conjunction with this, an effective planning algorithm is introduced, which is valid both for mobile robots and manipulators. Simulation results show the efficiency of the method.

Introduction

Planning collision-free robot motions in the presence of workspace obstacles is a major problem in robotics. Future robotic systems will execute complex tasks in clustered environments, and therefore the automatic generation of safe movements is a key point in providing robots with increasing autonomous capabilities. Most existing approaches fall into two main categories:

- (i) *continuous* motion planning, which relies on the use of obstacle distance functions to guide the motion [1,2,3,4,7,8]. In a relevant number of cases, this is obtained by modeling the robot workspace as an *artificial potential field*, in which the target is an attractor and the obstacles act as repulsors;
- (ii) *algorithmic* motion planning, based on the consideration of the *free configuration space*, i.e. the space of all robot configurations which do not yield interference with any obstacle [5,6]. Once this space is obtained, problem resolution can be reduced to a graph search.

It should be emphasized that algorithmic motion planning, though important for its exact nature, requires a great computational effort for obtaining the free configuration space. Use of artificial potential fields is an appealing alternative, due to their relative simplicity and to the generality of the approach. Conversely, the main drawback of these methods is the generation of local minima in the total field, which may cause the planning algorithm to fail.

The approach here presented is to place *vortex fields* around obstacles, so to force the robot to turn around them for reaching its destination. No local minima arise in the potential field, thus allowing the planning algorithm to converge. Simulation results show the effectiveness of the proposed technique.

Artificial Potential Fields

For a robot with n degrees of freedom moving in an m–dimensional cartesian workspace with obstacles, the *path planning* problem is formulated as follows: given a start location S and a goal location G in $\mathbb{R}^m$, find a path in the configuration space $\mathbb{R}^n$ giving a collision-free motion from S to G. This formulation is valid both for mobile robots and fixed-base manipulators; in the former case, the start and the goal must be intended for one representative point (e.g. the center of mass), while in the latter they specify end-effector positioning. The artificial potential approach consists in altering the topology of the robot workspace in order to plan its motion. In existing approaches, the addition of *attractive* valleys and *repulsive* peaks gives the required total field.

For simplicity, the case $m = 2$ (i.e. planar motions) will be considered in the following. Since the goal is one point in the cartesian space, one simple candidate attractive potential is a circular paraboloid with vertex in G (of coordinates $\mathbf{p}_G = (x_G, y_G)$). For a generic point P in the robot workspace, with coordinates $\mathbf{p} = (x, y)$, the attractive potential is $U_a(\mathbf{p}) = \frac{1}{2}\, k_g\, \mathbf{e}^T\mathbf{e}$, where $\mathbf{e} = \mathbf{p} - \mathbf{p}_G$ and k_g is a positive constant. The gradient of U_a w.r.t. $\mathbf{p}$ is $\nabla_\mathbf{p} U_a = k_g\mathbf{e}$, so that its modulus is proportional to the distance from the goal.

Motion planning can be performed on the basis of artificial potential fields in two conceptually different manners. Consider for example the case of absence of obstacles, i.e. a purely attractive potential field. First a *force control* approach may be used [3,7] considering the antigradient field $-\nabla_\mathbf{p} U_a(\mathbf{p})$ as a fictitious cartesian force field $\mathbf{F}(\mathbf{p})$ acting on the robot representative point. The resulting generalized forces are then evaluated as $\mathbf{T} = \mathbf{J}^T\mathbf{F}$ (where $\mathbf{J}$ is the robot Jacobian matrix), and dynamic evolution produces motion towards the destination.

As a second choice, a cartesian displacement in the negative gradient field direction may be specified as $d\mathbf{p} = -\nabla_\mathbf{p} U_a(\mathbf{p}) = -k_g\mathbf{e}$, so to give the maximum decrease for U_a. In the case $m = n$ this can be realized by choosing $d\mathbf{q} = \mathbf{J}^{-1}d\mathbf{p}$, while in redundant cases ($m < n$) generalized inverses can be used.

The first method, though effective, is somehow questionable due to unnecessary inclusion of the moving body dynamics in a purely kinematic problem †. This requires *(i)* knowledge of the robot dynamic model, and *(ii)* integration of the equations of motion. Besides, some *damping* procedure must be provided near the goal to avoid wandering due to residual kinetic energy. On the other hand, the second method requires kinematic inversion, which is computationally intensive.

An alternative approach is to plan motion *directly* in the configuration space: generalized coordinate displacements are generated through an optimization process of the potential function as a function of $\mathbf{q}$. To this aim, the gradient vector of the potential field U_a w.r.t. $\mathbf{q}$ is needed. Being

$$U_a(\mathbf{q}) = \frac{1}{2}\, k_g\, (\mathbf{f}(\mathbf{q}) - \mathbf{p}_G)^T(\mathbf{f}(\mathbf{q}) - \mathbf{p}_G) \Rightarrow \nabla_\mathbf{q} U_a = k_g\mathbf{J}^T\mathbf{e}. \qquad (1)$$

† Indeed, the inclusion of dynamics at the motion planning level is not motivated in this case, since no actuator limitation or time/energy minimization is considered.

setting $d\mathbf{q} = -k_g\mathbf{J}^T\mathbf{e}$ yields the maximum decrease in $U_a(\mathbf{q})$ (the steepest descent method). A line search procedure may be included to better convergence, naturally preventing oscillations about the minimum point.

Coming to obstacle modeling, consider the case in which a safe path for a single point is to be planned. This may be the case of a navigation problem, in which the mobile robot is represented with one point, or the end-effector motion planning for an articulated arm. Link interaction for this case will be considered later. Some features are to be guaranteed for the repulsive field $U_r(\mathbf{p})$:

- the field should go to infinity at the obstacle surface to prevent collision;
- it should have a limited range of influence, so not to affect the robot's behaviour far from the obstacle;
- $U_r(\mathbf{p})$ and its gradient must be continuous;
- the obstacle contour should be accurately modeled, not to cut off safe workspace regions.

An early proposed potential class possesses spherical symmetry, and is particularly suited to handle point obstacles (e.g. singularities in the workspace) and radially simmetric objects. Assume that a point obstacle is located in A, with coordinates $\mathbf{p}_A = (x_A, y_A)$. An example of repulsive potential of this class is

$$U_{r1}(\mathbf{p}) = \frac{1}{[(\mathbf{p} - \mathbf{p}_A)^T(\mathbf{p} - \mathbf{p}_A)]^\gamma}, \qquad (2)$$

in which γ is a real positive number. This function has an hyperboloidic profile, i.e. goes to infinity as the distance from A approaches zero, and fastly decreases as it augments; this behaviour is emphasized for higher values of γ. Potential (2) can be easily modified for the case of obstacles with center in A and maximum radius $r > 0$, by letting it go to infinity at a distance r from A.

Planning is made according to the total field U_{t1} obtained as superposition of the attractive potential U_a and the repulsive one U_{r1}. It is easily shown that, due to the circular shape of the isopotential contours of U_{r1} and to their greater curvature than those of U_a, no local minima arise in U_{t1}. This property may be preserved, under suitable hypoteses, also in the case of multiple disk obstacles [4].

The major drawback of spherically symmetric repulsive potentials is their limited relevance in practical situations. If a non-disk obstacle is to be modeled, it is often impossible to encircle it in a spherical contour without a considerable reduction of the safe workspace: for example, this is the case of a long thin rod placed across the SG line. A number of alternate repulsive potential functions have been built to overcome this problem.

The first to be proposed [3] was the FIRAS function

$$U_f(\mathbf{p}) = \frac{k}{2}\left(\frac{1}{d} - \frac{1}{d_r}\right)^2 \qquad 0 < d < d_r, \qquad (3)$$

in which d is the minimum distance of P from the obstacle, and d_r is the range of influence of the function. When a polygonal obstacle is given, the isopotential contours are composed by rectilinear pieces (parallel to the sides of the polygon) connected by circular arcs. The presence of zero-curvature tracts for any value of d is responsible for the generation of false minima far from the obstacle.

To avoid this problem, the isopotential contours should assume a circular shape far from the obstacle, while following the obstacle geometry close to it. In this spirit, an artificial potential function U_{r2} was introduced in [8], which improved the convergence properties of the planning algorithm. The proposed isopotential contours change from elliptical near the obstacle to circular away from it, thus preventing local minima to arise at large distances.

Two remarks are in order at this point. First, since isopotential contours are elliptical near the obstacle, U_{r2} is only suited to model *oblong* objects, i.e. having one largely dominating dimension. For example, a triangle-shaped object is well modeled by the FIRAS function (3), while circular or elliptical contours would be unsatisfactory. As a matter of fact, the superiority of the FIRAS function in accurate obstacle modeling is to be acknowledged.

Furthermore, it must be realized that in [8] local minima are not completely discarded, since repulsive contours near the obstacle have lower curvature than attractive ones. A sophisticate stepsize selection procedure is then devised, which should guarantee "jumping" of the local minimum depression. However, undesirable large steps may be forced, due to the possibly wide extension of this depression. Consider again the case in which a thin rod is placed orthogonally across the SG segment. The plot of the total field U_{t2} is reported in Figure 1a, while the contour plot of Figure 1b evidently shows the existence of a local minimum with a large basin of attraction, which is impossible to jump without hitting the obstacle.

Vortex Fields

The idea of placing vortex fields around workspace obstacles is generated by simple considerations. In fact, in order to reach its destination, the robot must not only *avoid collision* with those obstacles which obstruct its way, but more properly *turn around* them. In this sense, though repulsive potential functions guarantee obstacle avoidance, they can prove insufficient even in simple situations. As opposite to this cautious approach, vortex fields embody a more "aggressive" path planning technique.

To introduce this concept, consider first the case of a point obstacle located in the origin O of the xy coordinate system. The *vortex* field is defined as

$$\mathbf{V}(\mathbf{p}) = \begin{bmatrix} V_x \\ V_y \end{bmatrix} = \begin{bmatrix} \dfrac{-y}{x^2+y^2} \\ \dfrac{x}{x^2+y^2} \end{bmatrix}. \qquad (4)$$

This field assigns in each point P a vector which is tangent to the circle with center in O (that is the corresponding isopotential contour of U_{r1}), is oriented in the counterclockwise direction, and has modulus inversely proportional to the square of its distance from O, so to rapidly decrease as P moves away. As in fluid dynamics, $\mathbf{V}(\mathbf{p})$ is to be interpreted as a *velocity* field.

The primitive function U_v of the linear differential form $V_x dx + V_y dy$ is not globally defined. In fact, V_x and V_y are defined over a set which is not simply connected (O must be removed), and the integral of the form over a circle with center in O is nonzero. As a result, U_v is a multi-valued function, and in particular it is obtained as $U_v(\mathbf{p}) = \arctan(y/x) + c$, in which c may assume infinitely many values. As Figure 2a shows, U_v represents an helical surface with axis orthogonal to the xy plane in O. In Figure 2b the isopotential contours of the function are reported: as expected, they are not closed curves.

Vortex fields for the case of nonspheric obstacles can be built in a straightforward fashion with reference to the FIRAS potential function (3), which provides accurate modeling of the obstacle surface. Hence, the vortex field assigns in any point P a vector which is tangent to the corresponding isopotential contour of U_f, and has modulus inversely proportional to the distance from O.

As already said, the function U_v can be considered as a potential only *locally*. However, this is not to be regarded as a problem, since the motion planning algorithm is directly defined on the basis of the vortex field, while its primitive function only aids geometric intuition. When U_v is added to an attractive potential, the resulting total potential U_{t3} assumes the shape of Figure 3a. In this case, the isopotential contours shown in Figure 3b provide a more useful representation, since their direction is orthogonal to the gradient of U_{t3} in any point. Even if the total potential field does not go to infinity as the obstacle is approached, it is apparent that a proper choice of the helicoid slope will guarantee obstacle avoidance, as simulations will show.

Some remarks are mandatory at this point. First, when the obstacle has been avoided, a vortex removing procedure has to be devised, since otherwise the robot would continue to turn around the obstacle. This is accomplished by considering the angle α between the attractive vector and the vortex vector. It is easy to see that, as the robot circumvents the obstacle, this angle decreases till zero (see Fig. 4). At the point Q where this happens, the vortex field can be discarded, since the QG line is free. Note that even if this procedure does not introduce discontinuities in the gradient direction, its modulus would experience a jump at Q. To avoid this problem, the vortex field contribution can be multiplied by $\sin\alpha$, so to approach zero with continuity as the "scissors" formed by the attractive and the vortex vector close.

Another critical point is the selection of the direction of vortex rotation. While for mobile robots this may affect only the length of the generated path, in the case of fixed-base manipulators a bad choice may even prevent algorithm convergence. In fact, since the robot has a fixed base, some movements may bring the linkage to collide with the obstacle. A possible way to select the direction of rotation is to privilege *folding* over *stretching*, i.e. to orientate the vortex toward the robot base. This choice could sometimes prove not optimal, but will provide safe path generation even in situations in which the repulsive potential approach fails.

Finally, in the case of articulated manipulators, link interaction has to be taken into account. Consider for simplicity the case of a single obstacle. A common approach is to tackle this problem by identifying, at every instant, n points L_i — one for each link — which are at minimum distance from the obstacle. If a force control approach is used, each point L_i is subject to a force $\mathbf{F}_i$ generated by the obstacle potential field. The total torque arising at joints is obtained as

$$\mathbf{T} = \mathbf{J}^T\mathbf{F}_e + \sum_{i=1}^{n} \mathbf{J}_i^T\mathbf{F}_i, \tag{5}$$

where $\mathbf{F}_e$ is the force acting on the end-effector, and $\mathbf{J}_i$ is the Jacobian matrix of the kinematic function relative to point L_i. Equation (5) clearly shows that, when an articulated arm is considered, the absence of local minima in the total potential field does not guarantee convergence. In fact, even if $\mathbf{J}^T\mathbf{F}_e \neq \mathbf{0}$, the total torque $\mathbf{T}$ may be zero, due to the presence of the second term in (5). Such a situation occurs in one of the examples reported in the next section.

Since an optimization approach is pursued here, motion is planned in the configuration space in the direction of the gradient of a "virtual" total field $U_T(\mathbf{q})$ which takes into account end-effector as well as link path planning. This is simply obtained as

$$\nabla_{\mathbf{q}} U_T = k_g \nabla_{\mathbf{q}} U_{t3} + \sum_{i=1}^{n} \mathbf{J}_i^T \nabla_{\mathbf{p}} U_v \Big|_{L_i}, \tag{6}$$

in which $\nabla_{\mathbf{p}} U_v \Big|_{L_i}$ is the gradient of the vortex potential as experienced by each point L_i. Note that these gradients are not obtained through a differentiation; in fact, they are *directly* defined by the vortex field in the point.

Simulation Results

Two examples were worked out to test the proposed method, using a 3R planar manipulator. In the first example, a thin rod is placed across the *SG* line, and a repulsive potential gives a total field with a large depression in front of the obstacle, as in Fig. 1b. Figure 5 shows that the robot stops in the associated local minimum, and the planning algorithm fails. Instead, a collision-free path is obtained by placing a vortex field around the obstacle (Fig. 6). For any point in the range of influence of the obstacle, the vortex field is tangent to the isopotential contour of the FIRAS function (3). The direction of the vortex is chosen according to the *folding* strategy outlined in the previous section, that is towards the base of the robot.

In the second example, a disk obstacle is placed in the robot workspace. The line connecting S and G does not intersect the obstacle, so that the end-effector path is free, but collision of the manipulator linkage is possible. Figure 7 shows the unsuccessful performance of the planning algorithm when the obstacle is modeled with a repulsive function. Due to link interaction with the obstacle, the manipulator stops at a point where there is an equilibrium between the attractive field experienced by the end-effector and the repulsive action on the last two links. The positive outcome obtained using a vortex field is reported in Figure 8. Again, the rotation direction is chosen as outlined in the previous section. The improvement obtained with the proposed technique is evident.

Finally, two simulations were run in order to show the applicability of the vortex method in more complicated situations. Figures 9 and 10 show the

performance of the algorithm when a collision-free path is to be planned for a mobile robot in the presence of multiple obstacles. Interesting issues about the vortex direction selection in this case are not discussed for shortage of space.

Conclusions

A new method for planning collision-free robot motion in a structured environment has been presented. While previous approaches modeled obstacles by means of repulsive potentials, resulting in the generation of false minima, it has been shown in this paper that a proper use of vortex fields allows to overcome this problem. In conjunction with this formulation, an effective planning algorithm has been proposed, which is valid both for mobile robots and articulated manipulators. This technique is further motivated by the simplicity of the approach and the limited computational burden.

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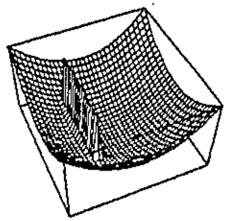
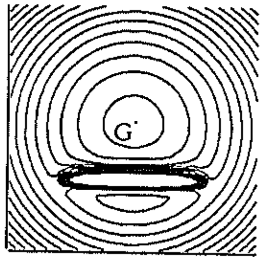


Fig. 1 – (a) Total field U_{t2};



(b) Contour plot with local minimum.

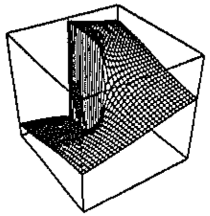
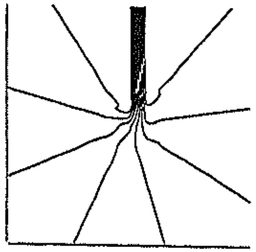


Fig. 2 – (a) Vortex function U_v;



(b) Contour plot.

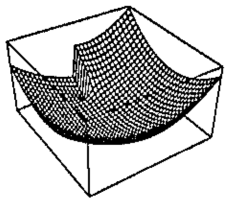
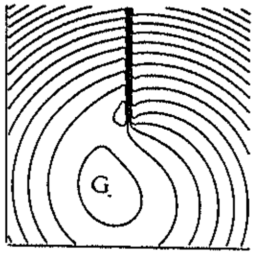


Fig. 3 – (a) Total potential field U_{t3};



(b) Contour plot: no local minima.

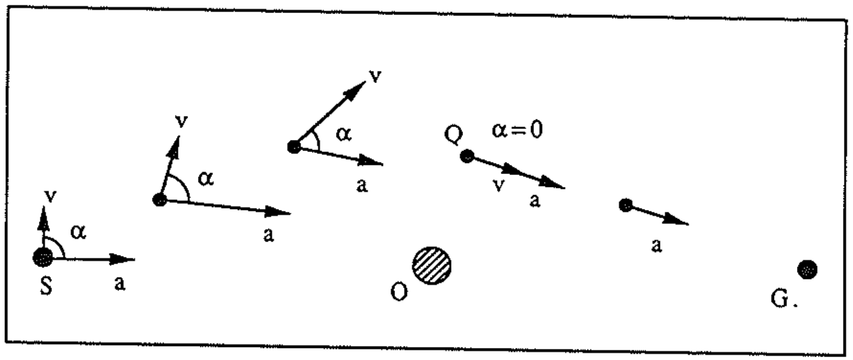


Fig. 4 – Vortex discarding procedure.

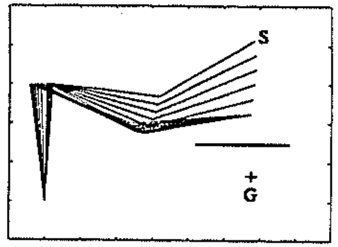


Fig. 5 – Ex. 1: with a repulsive field.

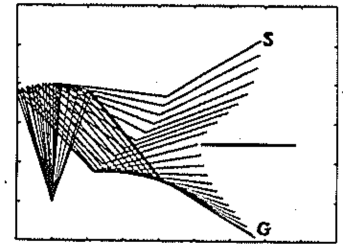


Fig. 6 – Ex. 1: with a vortex field.

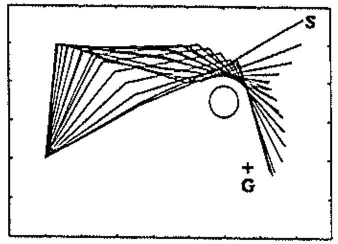


Fig. 7 – Ex. 2: with a repulsive field.

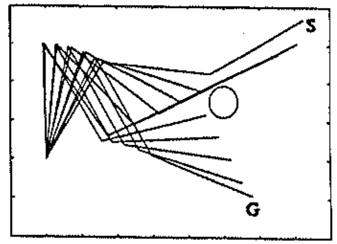


Fig. 8 – Ex. 2: with a vortex field.

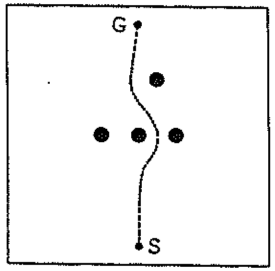


Fig. 9 – Ex. 3: multiple disks.

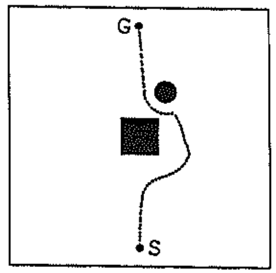


Fig. 10 – Ex. 4: generic obstacles.

S. Stifter and J. Lenarčič (eds.)

Advances in Robot Kinematics

With Emphasis on Symbolic Computation

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Preface

Advances in Robot Kinematics is a series of specialized international workshops organized every other year. Its objective is to provide a regular forum for researchers working in robot kinematics and to stimulate new directions of research by forging links between robot kinematics and other research areas.

The series of workshops has been established within the framework of the *Alpe Adria Program*. The Alpe Adria Program consists of a cooperation on several levels between European countries adjacent to the Alps or the Adriatic Sea.

The first workshop in this series took place in Ljubljana (Yugoslavia) on September 1988 and was organized by the Jožef Stefan Institute. Invited speakers, including many leaders in the field, discussed a wide range of topics on robot kinematics covering the whole spectrum from theory to practice. An international committee of specialists in the field of robot kinematics has been established to guide the organization of future meetings and other activities, including recommendation of world-wide scientific cooperation, promotion of new publications, distribution of relevant information, and standardization of notation, nomenclature, and methodologies.

The second workshop was jointly organized by the Research Institue for Symbolic Computation (Linz, Austria) and the Jožef Stefan Institute (Ljubljana, Yugoslavia). It was held at the University of Linz (Austria), September 10-12, 1990. The main focus of the second workshop was again to cover all aspects of robot kinematics, both in theory and in experimental implementations. Special emphasis was put on the investigation of symbolic computation techniques for problems in robot kinematics. While the first meeting had only invited lectures, this one included mainly contributed presentations. Almost 130 papers were submitted, out of which only 53 could be accepted (due to time limitations). The plenary lecture was presented by Bernard Roth from Stanford Unversity (USA). Four invited lectures by Jorge Angeles from McGill University (Canada), Marc Gaetano from INRIA at Sophia Antipolis (France), J. Michael McCarthy from University of California at Irvine (USA), and Bud Mishra from New York University (USA) gave an overview on latest results in robot kinematics and underlying symbolic computation techniques, respectively.

An award for the best student paper has been jointly won by G.S. Chirikjian from California Institute of Technology at Pasadena (USA) and G. Oriolo from Universita di Roma "La Sapienza" (Italy).

It has been decided in Linz that the next workshop will take place in Ljubljana (Yugoslavia) in July 1992. We believe that the third workshop will again, as the first two, provide an informal and productive atmosphere that will form the basis for valuable scientific contributions of Advances in Robot Kinematics.

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Linz, September 1990.

Contents

Scientific Committee xi

Introduction xiii

1 Invited Papers

A Scale-Independent and Frame-Invariant Index of Kinematic Conditioning for Serial Manipulators *2*
J. Angeles

Computer Algebra Systems: New Trends *10*
M. Gaëtano

Dexterous Manipulation: a Geometric Approach *17*
B. Mishra

2 Modeling and Computation

Adaptive Grid for Autonomous Robot, Environment Modeling *28*
V. Boschian, A. Pruski, C. Laurent

Industrial Robots: Application of a Rational Solution for the Direct and Inverse Dynamic Problem *37*
F. Casolo, R. Faglia, G. Legnani

Algorithmization of Kinematic Modelling of Industrial Robots *47*
G. Gogu

Imaginary Kinematics *55*
P. Kovesi

An Efficient Computational Method of the Jacobian for Robot Manipulators ... *63*
C.-L. Li, A. Hemami, T.S. Sankar

On Determining Parameters of the Twist-Axis for the Finite Displacement of a Body *71*
I.A. Parkin

A Summary of the Theory and Application of the Conics Method in Robot Kinematics *81*
D.R. Smith, H. Lipkin

Kinematic Modelling of Tasks Under Constraints. Application to Fine Motion and Calibration *89*
T. Tran, A. Giraud

Modal Formulation for the Dynamics of Flexible Manipulators and Large Space Structures *99*
E. Wehrli, P. Coiffet