INDUSTRIAL RESEARCH INSTITUTE FOR AUTOMATION AND MEASUREMENTS

PIAP

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INVERSE KINEMATICS FOR REDUNDANT MANIPULATORS.

STATE OF THE ART

Job was realised within:

INGRID-PECO Project

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the job has been done by:

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CONTENTS

1. Introduction - presentation of the topic

Topic is being solved as a part of joint project INGRID in TELEMAN programme, financed by European Community. The main goal of the project is to design an intelligent gantry robot applicable and to be used for distribution a nuclear materials. The whole work is divided into four groups of problems:

- a remote handling workstation - based on standard workstation which should be designed as a monitoring and control system for the robot and all co-operating with it devices (supervisory central station),
- control system - hardware and software making provision for direct half autonomic control of the robot and its subsystems, control of gantry, control of tools and communication with external sensoric systems. The system is integrated as a logic structure of supervisory control station,
- generic devices - robot's manipulator (6 DOF, PUMA-like), gantry with a crane (5 DOF: forward-back, left-right, up-down, and two rotary kinematics pairs), camera, sensors of force and other co-operating devices,
- remote handling system - project, implementation and testing of activity procedure - that procedure is designed as a group of actions of robot system demonstrating, its possibility of work at production cell and distribution of radioactive materials. It includes also monitoring of radiation level and chemical activity of materials at cell, decontamination and clearing of equipment and the cell itself (with removing the wastes and theirs collecting into special container), assembling and disassembling tools used at the cell, inspection of the cell with TV system.

Among the tasks of the first group is (among other things) a path planning system (PPS). This topic has been solving since certain time by CRIF/WTCM in Brussels. There was designed GPPS (Global PPS) - path planning system of working tool in external co-ordinates, exactly this system works in basic configuration of the cell co-ordinates. As a hardware platform for GPPS there was chosen a Silicon Graphics workstation. There also can be used SUN, IBM, HP stations, but under condition of possibility to work with fail of programs for modelling and simulation robot programs - ROBCAD, which compose the software environment for GPPS. ROBCAD has implemented counting functions of direct kinematics for a chain of max. 32 degrees of freedom and inverse kinematics for a chain of max. 6 degrees of freedom. As far as has been arranged in the INGRID project the robot has 6 DOF and the gantry has 5 DOF. So the system has altogether 11 DOF. It means this is a redundant manipulator. Such an inverse kinematics ROBCAD can not calculate. The CRIF's team solved the problem temporarily including disconnection the gantry and the robot during calculation of direct kinematics. This method gives very good final effect but it has also a big weak points. At that way are not used possibilities and advantages which are given by robot's redundancy according to smoothness, agility and handiness at working. Achieved movement is not optimal from energetic point of view.

This way makes more difficult realisation tasks of surrounding a trajectory (path). At the same time there are known various methods of solving inverse kinematics for redundant robots. Lot of information about these works we can find in professional journals, books or reports from conferences. Authors use to offer very various methods. There is no agreement which way would be the best, as e.g. for non redundant robots with 6-DOF. There are also non checked, tested and ready to use solutions for substantial group of manipulators. At the end there are no complete, fully formalised algorithms. The task to find just a general solution of

inverse kinematics for redundant manipulators as a part of joint project INGRID goals has been assigned PIAP. So now there is necessary to do as follows:

- review and analysis of some items of literature concerning inverse kinematics of redundant robots,
- choice a few real methods useful for solving the reverse kinematics
- simulation implementation of prepared algorithms
- simulating tests, evaluation of suitability and choice the algorithms applicable for practical use in the project
- connection worked out and chosen solution with GPPS and making a real investigations

This is the report of the first task mentioned above.

2. Used materials

Looking for papers and books to prepare a review of literature the PIAP's researchers solving this topic had two main sources of knowledge.

1. CRIF's library, which has very wide collection of conference reports. PIAP's workers used an opportunity in choosing an interesting papers and they made xerocopies of many of them.

2. Main library of Warsaw University of Technology which (as we have found) has the biggest collection in Poland of current konowledge in the domain of solving task.

The other sources of knowledge and information at a few other Universities, Research Centres have not been used because time of waiting for copies and books is too long.

So the chosen items for study and analysis are from following editions:

Journals

- IEEE Journal on Robotics and Automation
- IEEE Transactions on Automatic Control
- IEEE Transactions on Man-Machine Systems
- IEEE Transaction on Robotics and Automation
- IEEE Transactions on Systems, Man, and Cybernetics
- Journal of Robotics Systems
- The International Journal of Robotics Research

Conferences

- ICAR Int. Conf. on Advanced Robotics
- IEEE/RSJ International Workshop on Intelligent Robots and Systems IROS
- IEEE Int. Conference on Robotics and Automation,
- Int. Symposium on Experimental Robotics
- ISIR Int. Symp. on Industrial Robots
- RoManSy Symposium on Theory and Practice of Robots and Manipulators
- SPIE's International Sympozjum on Optical Tools for Manufacturing

There is necessary to point that papers in magazines are much more precise and exact. In conference reports and papers there are usually very new informations, but they are mainly very general and practically just touch the problem. Their most important advantages are in the very current news. These informations use to follow in magazines or books (much more worked out), but unfortunately with the delay of many months or even years.

Analysed journals contained years 1987-1994 and only if it was necessary also previous years (in case of special interest or indication)

3. Described methods for solving inverse kinematics for redundant robots

The rule of collection the literature items.

As we mentioned earlier the main source of information about methods and algorithms used for solving the inverse kinematics problem for redundant robots there were papers.

All collected positions of literature have been divided into two groups:

The first one called basic (general), which consists of papers concerning the searched field and which shows real methods or theoretical bases to be solved.

The second group called complementary which consists of papers which allow to supplement the problems and to know problems very close to the main one. These are for example: solving inverse kinematics task for 6-DOF robots (also in closed form), way of presentation of robot and obstacles at its working area, and so on. In papers of this group can be found also information concerning different points of view on problem of generated trajectory and analysis of inverse kinematics.

This documentation contains a list of all papers which have been analysed with segregation into two above mentioned groups. For a few, as an example, we attached the results of analysis.

In this chapter there are extracted the groups of methods, which are presented in literature.

Basic general position.

- Many manipulators have singular configurations, in which some small moves of working tool needs a high speed in joints, physically not achievable. In articles [A4, A5] there is proposition to avoid these high speeds by including a redundant links and using an appropriate algorithm of the inverse kinematics. The statements (theorems) of that articles express (for very wide-spread inverse kinematics algorithms) a few basic interdependencies between the features of algorithm and its ability to solve the problems. These results have a practical meaning at controller designing for a redundant manipulators, particularly if for modification of trajectory is used a sensorical input in real time. These articles, using the topological arguments tell about a few limitations concerning area successful applications of inverse kinematics algorithms for point positioning and orientation. There was explained occurrence of singularity features and conditions of their existing, first for non redundant manipulators and then for redundant ones. There was considered the type of kinematics inversion methods, called "tracking algorithms", which depend only on the current manipulator configuration and the local properties of the path. For didactic purposes two categories of algorithms were introduced:
  - path inversion methods,
  - local inversion methods.

  Because the second group enable a real-time service of sensoric systems, this group was especially analysed. The most methods of local inverse base on repeating solutions of different relations between joint space co-ordinates and operational space co-ordinates. Varied methods differ the way to finding the only one velocity ϑ' from among of solutions equation $df(\vartheta'(t)) = x'(t)$. The most prevailing methods are shown in a short way.

- In [A15] a new method, called OM - offset modification - was presented. It works by modifying the link offset values of manipulator (e.g. Denavit-Hartenberg parameters) until it is possible to derive closed-form solution of inverse kinematics. As result we receive a new manipulator. Solution of inverse kinematics for this model manipulator is a base for finding solution for target manipulator. In this article was discussed an application of the OM method to various 6-DOF and redundant manipulators. As an introduction to this 10 other metods, proposed in various publications in last years were presented.

Geometric methods.

These methods aim to receive a closed form of inverse kinamatic solution for part of manipulator. There are different ways. One possibilty is to connect redundant joints into mathematics function. Then we obtain less unknow quantities or more equations. As a result of such algorithms is one set of values for nonredundant joints and much solutions for redundant joints. This mathematic functions describe possible configurations for redundant joints [A1].

In this group are included methods, in which part of joints are freezed (locked up). In such a way a new, created manipulator has less degrees of freedom and is non-redundant [A23]. For that manipulator we obtain one solution. For rest joints we accept positions from last pose, previous point of trajectory.

A specific variant of geometric method is OM algorithm, mentioned above.

Generally these methods are limited in practical implementation to manipulators with a small redundancy. A majority of computational examples based on 7-DOF, anthropomorphic manipulator (human arm like).

Pseudoinverse Jacobian methods.

It is the large group and contain the most of all literature positions. Main problem is: how to inverse a matrix NxM, when N<M. Already in the end of 70-ies Moore-Penrose generalized methods was proposed [A24]. Now there are also known a Greville- and Hastens-methods [A10]. First one is iterative. The second one uses the concept of biorthogonality.

Next works developed previous concepts. In [A7] authors proposed to use for Moore-Penrose method a minimum joint velosity norm as an additional criteria.

In [9] author present a method based on compact formulation technique, called Compact-Inverse. In this method it is assumed, that Jacobian matrix J has full rank m, then column of J are permuted such that the first m columns are lioneary independent. Then such matrix, by Gaussian elimination is transformed into a row-reduced echelon form. For this form a general solution is preparing. It use linear and nonlinear programming techniquec to obtain optimal result.

Task augmentation methods.

It is an alternative groups of methods again pseudoinvers. The main idea is to expand an invers kinematics task by introducting additional requirements. There can be:

- constraining position of manipulator links [a16],
- feedback linearization [B6],
- closed loop control reformulation of augmented inverse kinematics [A20],
- configuration control of redundant manipulators [A22].

Methods based on fuzzy logic technology.

It is a very young group of methods. They use an iterative technique. The inverse kinematic transformation of the positon and orientation from the task space into the joint space is performed by a closed loop algorithm based on fuzzy logic. The main problem is to determine general rules for define of direction joint angles changing in next step of iteration. An imporatnt feature of this method is the facility of incorporating linguistically expressed control strategies for manip[ulator self-motion into kinematic level of the robot controller.

Methods based on optimisation techniques.

In these methods a started internal position is assumed. Then an algorithm give succesive positions in direction a target solution. Main problem is the convergence of algorithms. Main feature is simple computer implementation. Actually there are proposed methods based on:

- Conjugate Gradient and Variable Metric concept [A11],
- Newton-Raphson algorithm [17],
- Simplex and Monitored Trial Increment search [A18].

APPENDIX 1

LIST OF LITERATURE

A. BASIC POSITIONS

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