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A MULTI-LINK MULTI-PURPOSE ADVANCED MANIPULATOR WITH A LARGE HANDLING HEMISPHERE FOR OUT-DOOR APPLICATIONS

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ABSTRACT

Multi-link articulated booms have a multitude of applications in civil engineering, e.g. concrete pouring, building maintenance etc., but also fire fighting. In the Kernforschungszentrum Karlsruhe (KfK) a new system with a multi-link articulated boom of 22.2 m maximum length and 6 rotary axes is under development in cooperation with Putzmeister-Werk. Our development is aimed at working the system like a large robot. Therefore a reprogrammable control system will allow for variable motions to perform a variety of preplanned handling tasks. A hierarchical control architecture was designed where the operator acts independently from machine details. This requires an elaborate man-machine interface which is based on a graphic display and a joystick. In an environment cluttered with objects which may hamper the moves of the manipulator an automatic search algorithm can be used to find a path for the tool center point (TCP) of the manipulator using a world model. This algorithm is based on a graph-method and will be described in detail. An interactive computer program was implemented to establish the world model by several methods. The paper describes mainly the basic methods for trajectory planning with collision detection and avoidance. It gives an overview over the whole project.

1. Project Overview

The KfK project EMIR (Extended Multi JoInt Robot) is connected to a joint project of several industrial companies and research institutions named "Advanced Handling Systems with Enhanced Flexibility", sponsored by the German Government /1/. As reported at this conference, a PUTZMEISTER[1] manipulator with 6 axes and 22.2 m reach will be tested at the IPA site, employing the AEG R500 control unit. At the Kernforschungszentrum Karlsruhe (KfK) a further manipulator with identical kinematics is mounted on a bridge (Fig. 1). In a basic effort a new control system is developed, including automatic path planning, obstacle avoidance, oscillation damping, and world model generation, employing the KfK experience from the nuclear field. The KfK-work on world models is also part of the mentioned joint project. This paper deals with the KfK-work. Some of the applications, as described in section 5, will be demonstrated on our site.

The three level hierarchical control system of EMIR is based on the 80286/287 processor family and local intelligence, communicating via a BIT BUS network.

The planning, programming, and control system runs in several operating modes, as shown in Fig. 2. It can easily be switched between hand-control and automatic mode.

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[1] PUTZMEISTER-WERK, D-7447 Aichtal 2

Under hand-control the user guides the manipulator in suitable coordinates by a joystick in a hand held box. The necessary software modules for coordinate transformation and interpolation are implemented on the control computer. Collision detection is done in parallel by the planning computer.

Ad-hoc programming includes automatic trajectory planning, collision avoidance, and interpolation. The required target can be indicated on the graphical display. The automatic mode executes the pre-planned and interpolated program. During execution the operator can change to a superposed hand control.

As interface between the planning system and the manipulator control we use a standardized software called IRDATA-code (DIN working committee in NAM-UA 96.1.2). This allows the test of available methods of robot programming. Off-line programming is done by defining user programs or macros, see /2/. This also applies to some pre-programmed special tasks like meandering across a plane etc., increasing the economic interest.

The problems and solutions presented in this paper deal mainly with path planning and kinematic configuration of the multi-joint robot in the presence of obstacles. Our solution is based on a world model. This can be established by a teaching process, moving the manipulator directly to relevant obstacle points. Another method developed by us uses a theodolite, electronically coupled to the main computer, and an interactive guidance program for the measurements. A main objective for these methods is cost reduction.

2. Description of Multi-Link Manipulator

The hydraulic driven manipulator is fixed to the ground by a jack with two hydraulic motors allowing for 360 degrees of rotation. The five joints are piston driven, part of them with a special gear consisting of two levers to achieve more than 180 degree rotation angle. The axes of these five joints are parallel and therefore constitute a kinematic redundancy in the boom plane. The overall workspace is a hemisphere of 22.2 m diameter. Depending on the application at the tip of the boom different platforms, grippers or tools will be mounted. The profiles of the links are of a special design which results in a small dead-weight of the structure but a great payload (1400 kg). The hydraulic oil is supplied by a pump with a power of 75 kW and is controlled by proportional electric servo-valves with a high mass flow rate and small pressure losses. This will yield a maximum speed of the tip of the boom of about 1.5 m/sec.

3. Problems of Far-Reaching Robots in Construction

Far-reaching robots of the type described present a number of problems quite different from those of conventional types.

3.1 Problems Resulting from Low Stiffness

From economic reasons, the stiffness of far-reaching systems is comparatively low. As a consequence we have to cope with gravity induced bending and an increased tendency for vibrations. With manual control the operator can compensate the inaccuracy from bending. For automatic control we have implemented a non-linear bending model with particular emphasis on the gear connecting piston rods and links. The model has been verified by an elaborated finite element program and by experiments.

To reduce vibrations, a dynamical model and damping provisions will be included into the control system. But also, as will be shown in section 4 of this paper, our configuration strategy in many cases will move a limited number of links at the front end only to achieve a certain goal. This helps to reduce the vibration energy brought into the system.

3.2 Problems Resulting from Hydraulic Drives

Due to the large payload, only hydraulic drives can be used with these types of robots. Basically here the velocity of the piston displacement can be controlled by the opening of an oil valve. Temperature dependent oil elasticity and the non-linear transformation from piston displacement to joint rotation, are important for the control system. Extensive modelling also indicates the possibility of a mutual amplification of piston and boom vibrations. Presently tests are underway on the control of the hydraulic drives.

3.3 Redundant Kinematics

Since the number of axes is greater than the degrees of freedom of the boom tip in space, we have the problem of redundant kinematics. There is therefore no definite backward transformation from cartesian coordinates to joint angles. Of course this allows for the introduction of additional conditions for obstacles avoidance.

The solution of the kinematic problem, considering also some aspects of the other problems described in this section, is a main topic of this paper and, therefore, will be elaborated in section 4.

3.4 Problems Resulting from Construction Applications

The use of far-reaching robots in construction means application in frequently changing environment. In most cases robots of this type are mounted on vehicles and often moved from one site to another one. This excludes a time-consuming teach-in of the required task and obstacle avoidance. Therefore automatic path and configuration planning in a simple and quickly generated world model is needed.

4. Trajectory Planning, Backward Transformation, and Collision Avoidance

The problems mentioned in the previous section and especially the questions arising from the kinematic redundancy required an integrated kinematic solution. This section will give a description of our method. To some extent it is different from solutions published so far. It consists, as indicated in Fig. 3 basically of a trajectory planner and a configurator. The trajectory planner generates a path, by which the TCP can be moved stepwise from a starting position to a predefined destination. The trajectory planning could be done by the human operator influencing the TCP-motion by the joystick, or it can be done automatically. The configuration of the boom on the other side is a cumbersome process and should be done automatically.

4.1 Automatic Trajectory Planning

The problem of automatic trajectory planning is finding a practical route where to move a defined point of a connected, multilink assembly without collision from a present position to a chosen target position. Generally the defined point is the boom tip, the end of the kinematic chain.

4.1.1 Present State of Knowledge in Trajectory Planning

Some work can be found in the literature on trajectory planning for kinematic chains of the present type. Most path planning work is concerned with the movement of an unconnected single finite polyhedron between obstacles. The earliest path planning methods use cell type procedure like the Lee-Algorithm /3/. Here the operating range is subdivided into planar (or cubic) cells, which could be empty, full or partly filled. Partly filled cells are further divided down to a predefined scale, work /4/, /5/, /6/.

Related and less time-consuming are methods for modelling the free space to simple geometric shapes, better fit for path planning, and model their connections in a graph structure. Here should be mentioned /7/. Lozano-Perez /8/ introduced a method to shrink the moving body to a point and to increase the obstacles correspondingly. This permits the transformation of the problem to well known methods of path planning for a geometric point. The problem of this method arises from the non-linearities introduced by rotation of the moved body. However, in a heroic effort Donald /9/ created a solution for a 6 dof PUMA robot.

Finally there should be mentioned local methods where standard trajectories can be corrected by sensor information (surface following), /10/, /11/ are examples. None of the mentioned methods could directly be applied to our problem.

4.1.2 The Presented Path Planning Method

Our manipulator combines five axes of a basically planar kinematic chain with one axis for three-dimensional rotation. Therefore, it seemed advantageous to separate to some extent the kinematically redundant planar problem from the three-dimensional case. 3D-motion therefore will be treated as a sequence of 2D-motions.

The complexity of the planar problem requires a global path planner, therefore local corrections of a standard path may not suffice. Cell methods, free space modelling, and shrinking the manipulator, on the other side, are too time consuming for the complexity of our problem.

Therefore, we have chosen the simplest method of all, the trajectory planning for a geometric point in the presence of convex polygonal obstacles. The only modification is to plan this point/trajectory by a given distance away from the obstacles and check for collision. This leaves the burden of the work to the subsequent backward transformation or configuration of the kinematic chain. As will be explained in section 4.2, a TCP trajectory is used for the configuration process anyhow. Therefore, the trajectory planning is a byproduct without much additional computational costs.

The planning of a planar trajectory for a moving point is a well-known problem. We use here the work of /12/, based on the supporting segments. As explained in Fig. 4 supporting segments are straight lines between the vertices of the polygonal obstacles with extreme gradients. According to /12/ all supporting segments are arranged in a binary heap. This structure has to be generated once and allows for the calculation of shortest connections for arbitrary and changing combinations of starting and end points.

4.2 Configuration Planning (Backward Coordinate Transformation)

While the tip of the manipulator is positioned at a series of subsequent positions on the trajectory defined according to section 4.1.2, all links have to be placed collision-free and without a smooth movement of their axes. The relative angles between links are subject to restrictions which must be taken into account. The obstacles could have any convex polygonal shape.

4.2.1 Present State of Knowledge in Configuration of Redundant Kinematics

All known methods solving the backward transformation for a system with redundant kinematics use a stepwise linear correlation between the cartesian position of the manipulator tip and the angles by means of the Jacobian of the transformation matrix. The non quadratic shape of this matrix prevents the usual inversion. Methods to circumvent these problems are the Moore-Penrose Pseudoinverse /13/, /14/ or the 1-Inverse /15/. These solutions allow for the introduction of additional constraints as presented by the obstacles or the angular limitations.

The Jacobian-based method allows for an elegant solution for some of these problems. Their main disadvantage is their local character, since their range of validity is limited to a close proximity of the present state. This requires not only a very small step size, there is also no general solution to prevent the manipulator from getting stuck by an unfavorable combination of obstacles and angle restrictions.

4.2.2 Presented Method for Global Configuration

To achieve global configuration, we introduced some heuristic expert knowledge. This refers basically to two modes:

1. For operation in a certain neighbourhood of the manipulator base or if no obstacles are present it is advantageous to fold the links not needed. This results in what we call the "compact operation mode" (COM). Also it allows a complete unfolding and folding of the manipulator from and to transport configuration. As explained by Fig. 5 here always only two axes are used fo reaching the target. The COM also allows for some local collision avoidance mechanisms.

2. For operations more distant from the manipulator base and with an increased probability of obstacle interference we use a TCP trajectory between base and target as a guiderope for arranging the links. This we call the "guiderope mode" (GRM). An easy construction of the guiderope is possible due to the availability of the data structure of supporting segments as described in section 4.1.2.

   This placement includes provisions for

   - Maximizing manipulator reach Fig. 6 (a) by minimizing the distance C'B before attaching the next link,

   - Avoiding collisions Fig. 6 (b)

Excessive manipulator length after completion of link placement (Fig. 7) must be avoided by backward rotation of link No. 1 and, if necessary, link No. 2.

Criteria for changing from GRM to COM are "going backward" (TCP returns to base) and a point-trajectory between manipulator base and target point with no more than a single vertex. This indicates that the situation is simple enough to return to COM. This requires comprehensive testing in different scenarios.

4.2.3 Transition Procedures

These basic procedures for motion calculation are complemented by

- an interpolation procedure for transition between COM and GRM and vice versa,
- procedures to assist the unfolding/folding of the manipulator in restricted areas,
- procedures to assist the COM for operations below its base, including the relevant unfolding and folding (e.g. for work below bridge)

Global methods with a choice of problem specific tools require intelligent criteria when to change from one procedure to another one. Besides simple criteria like "going forward", "going backward", "working above base", "hitting angular restriction", "collision" etc. also the TCP trajectory is in use as an intelligent probe for the topological complexity of certain situations. Especially a simple criterium for the reconfiguration from the GRM back to the COM is derived from it (see 4.2.2).

Transition between COM and GRM or between GRM and COM is smoothed by a basically simple interpolator being called if any joint angle changes from step to step by more than a predefined amount.

While unfolding and folding from or to transport configuration with the COM in the proximity of obstacles, the sign of the angle between links No. 1 and 2 must be changed, Fig. 8. Special procedures are provided.

5. Applications

It is envisaged, that the KfK-EMIR-project will demonstrate a broad variety of application possibilities of the newly developed advanced manipulator. As a first application, in construction industries a control system which allows moves in cartesian or cylindrical coordinates with a collision detection for a conventional concrete pouring machine will certainly have success because of the simple use and safe operation. A preprogrammed macro which automatically meanders the pouring nozzle over a plane or an automatic concrete casing following system will improve operations. The manipulator also might be used as a highly flexible crane with a gripper for transport purposes in restricted areas (Fig. 9). Machines or even robots may be transported to the working position by our system. Then the manipulator may be considered as a carrier system the tools. These applications, however, require reliable safety systems.

Furthermore, we think that our system might be of profit for fire brigades. This also is the first application we will realize in the testbed in our laboratory. At the boom tip we shall mount a water spray gun with two axes for orientation of the nozzle, Fig. 10. Such a teleoperable system will increase performances in hazardous situations and will help to avoid risky situations.

6. Conclusions and Future Development

The presented manipulator system can demonstrate the portation of methods and techniques developed for industrial robots and for nuclear engineering to new applications and facilities. As described above the concepts for path-finding, trajectory calculation and backward tranformation are applied to hydraulicly driven manipulators working in a poorly structured environment.

A new approach to solve the trajectory planning and kinematic backward transformation of a system with 3 redundant axes in the presence of obstacles, integrating smoothly unfolding and folding operations, looks promising.

Such far-reaching robots will be applied to new missions, but it is necessary to improve the whole system as described. In future much more effort and attention will be given to user requirements for easier and safer operation with the manipulator. At KfK the future steps will deal with the addition of more external sensors to support the work in hazardeous situations and to improve the safety. Some of the new methods like collision avoidance will be applied to other manipulators. It is also intended to portate the implemented software tools to other applications.

7. References

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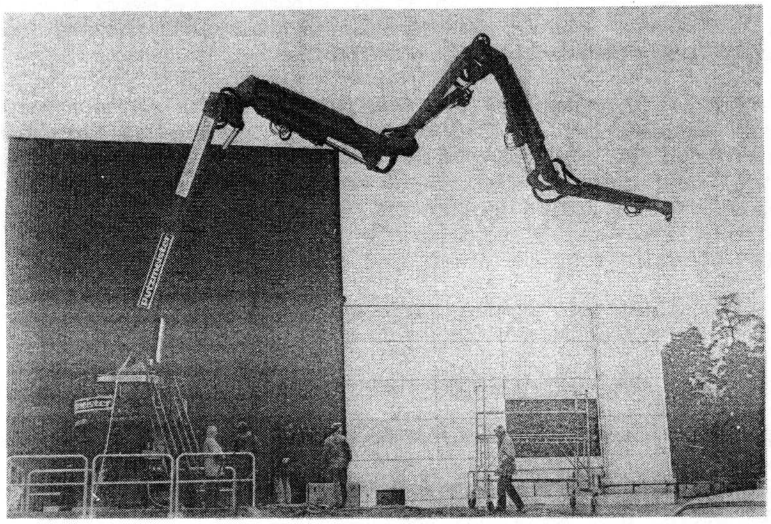
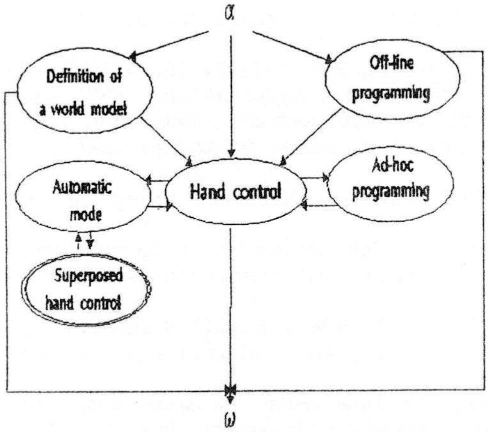


Fig. 1: Advanced manipulator with a reach of 22.2 m and 1400 kg payload



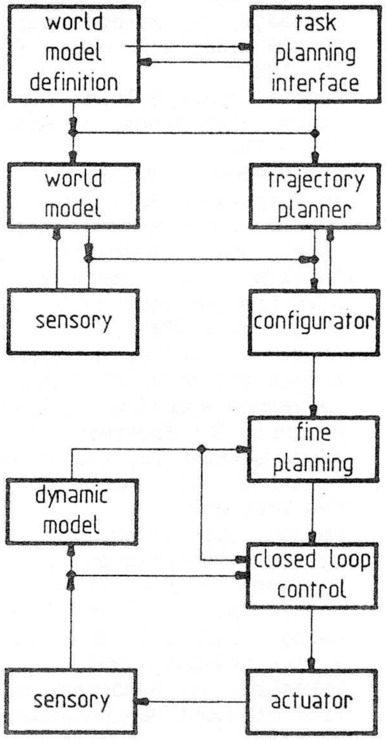


Fig. 2: Hand- and automatic control modes

Fig. 3: Overall control hierarchy

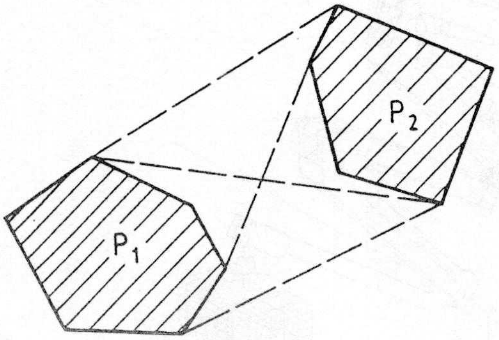


Fig. 4: Supporting segments (dashed lines) between polygons P_1 and P_2

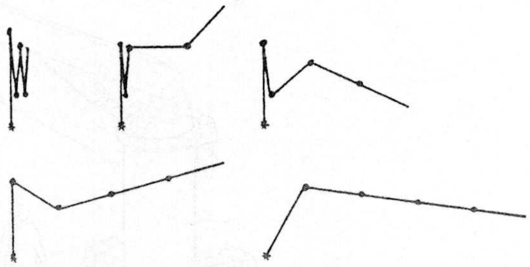


Fig. 5: Compact operation mode as a function of target distance

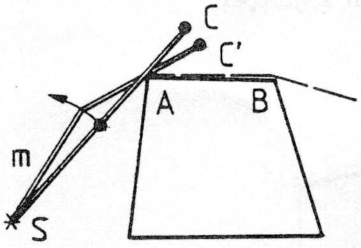


Fig. 6a: Guiderope mode maximizing reach

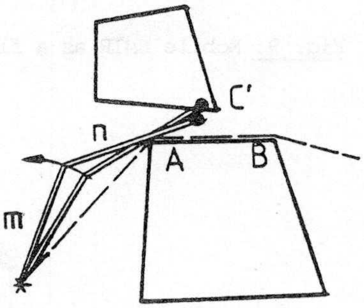


Fig. 6b: Guiderope mode avoiding collision

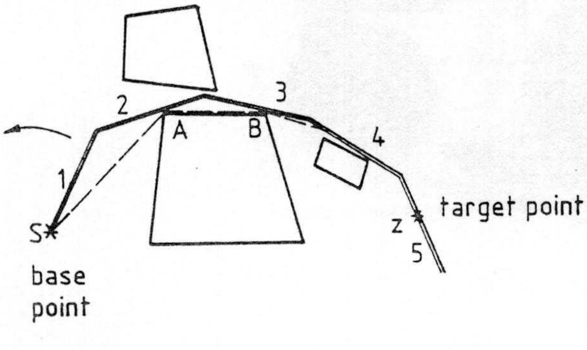


Fig. 7: Compensation of excessive manipulator length (rotating back link 1)

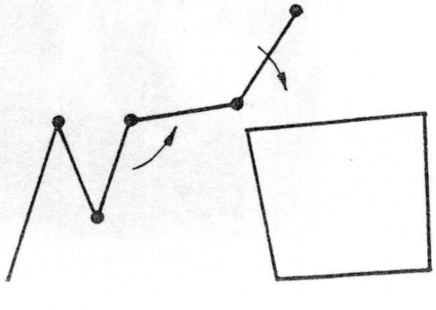


Fig. 8: Compact operation mode in the vicinity of obstacles

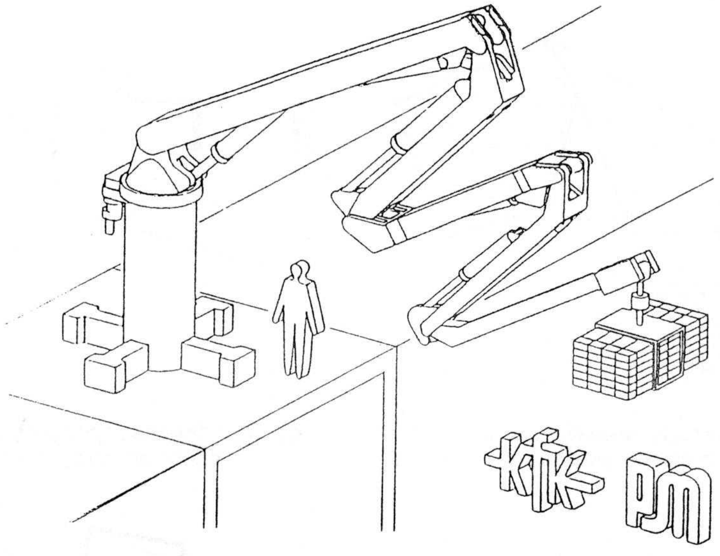


Fig. 9: Mobile EMIR as a flexible crane with a gripper

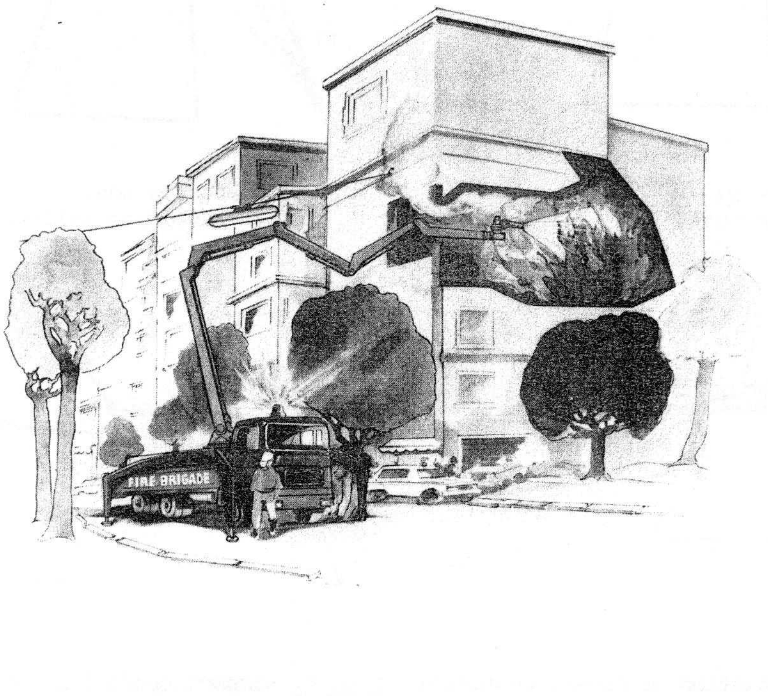


Fig. 10: Mobile EMIR with a water spray gun