AUTOMATED KINEMATIC EQUATIONS GENERATION AND CONSTRAINED MOTION PLANNING RESOLUTION FOR MODULAR AND RECONFIGURABLE ROBOTS*

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Introduction

Contrary to the repetitive tasks performed by industrial robots, the tasks in most U.S. Department of Energy (DOE) missions such as environmental restoration or Decontamination and Decommissioning (D&D) can be characterized as "batches-of-one," in which robots must be capable of adapting to changes in constraints, tools, environment, criteria, and configuration. Commercially available robots are optimized for a specific set of tasks, objectives, and constraints and, therefore, their control codes are extremely specific to a particular set of conditions. Thus, there exists a multiplicity of codes, each handling a particular set of conditions, but none suitable for use on robots with widely varying tasks, objectives, constraints, or environments.

Our approach to resolving this shortcoming is to develop a "generic code" that would allow real-time (at loop rate) robot behavior adaptation to changes in task objectives, number and type of constraints, modes of controls, and kinematics configuration (e.g., new tools, added module). The underlying framework consists of two major modules: (1) a novel constrained optimization solver for the general solution of under-specified systems of algebraic equations that is suitable for solving the inverse kinematics of kinematically redundant robots (e.g., manipulators, mobile manipulators) with no limitation on the number of joints and that can adapt to real time changes in number and type of constraints and in task objectives, and (2) a module that automatically generates the kinematics and motion equations to accommodate changes in kinematic configurations (e.g., change of module, change of tool, joint failure adaptation). Achieving such a unified resolution methodology and code, which does not exist today, is seen as one of the major enabling capabilities that would save the enormous amounts of human time currently required to program and set up specific codes for each particular robot, robot configuration, task condition, task environment, mode of operation, or behavioral objectives.

Approach summary

The underlying similarity of all of the inverse kinematics approaches that have been proposed is that they all use one of the two main techniques for resolution of under-specified systems of equations: generalized inverse-based approaches or augmented task space methods with "extended Jacobians," both having very significant shortcomings for application to systems where constraints and/or task requirements may change widely and rapidly (e.g., at loop-rate and/or on a sensor-based basis) during a single trajectory. In particular, each technique corresponding to a particular set of task requirements, optimization objectives and constraints also corresponds to a particular algorithm.

Our approach to the generalized inverse kinematics problem uses a novel formulation of the fundamental expression of the solution space to allow a constrained optimization approach that supports generalization, as well as deterministic computational time through analytical solutions (as opposed to iterative) to the possibly time-varying, multi-constraints system (see [1, 2]). The generalization capability arises from the calculation of specific solutions satisfying, simultaneously, the task requirement and all the constraints of a time step using a general Lagrangian-type constrained optimization scheme [3, 4, 5]. For the automatic generation of the kinematic equations, our approach is to generate the symbolic expressions for the forward kinematics expressions on-line from the geometric description of each joint/link of the manipulator provided by the Denavit-Hartenberg parameters. The expressions are derived by building the transformation matrices for each joint and subsequently for the overall system, and are simplified symbolically. The symbolic expressions are represented via a simple tree structure. The nodes of the trees represent operators and the leaves constants or variables. A selection of operators is provided, currently all unary or binary operators. Hence, each node has one or two child branches (or leaves). To then obtain the velocity equation's Jacobian expression on-line, our system automatically differentiates the forward kinematics expressions through application of the chain rule for each matrix element. A benefit of this symbolic differentiation approach is that the generation of the Jacobian is completely independent of the form of the forward kinematics expressions.

Illustrative problems

To illustrate both the dynamic re-computation of the Jacobian capability and the inverse kinematics resolution capability with multiple and time-varying constraints, a sample problem involving a 14 degrees-of-freedom (d.o.f) mobile manipulator with a non-holonomic constraint performing a hole-drilling task is presented. In Fig. 1, the (car-like) non-holonomic mobile platform is represented by the rectangle upon which is mounted a 9-joint manipulator. The trajectory followed by the end-effector is shown labeled in three sections: A, B, and C. First, the end-effector moves along the trajectory segment A to pick up a drilling tool, as shown in part (a) of the figure. The rectangular platform is initially facing right and backs up to the left in a shallow turn. The drilling tool is a 2-d.o.f. articulated tool (pitch and yaw). When the drill is connected, the Jacobian is automatically regenerated to incorporate the two extra links, bringing the total d.o.f., including the platform, to 14. Constraints are also active, including joint limits and the non-holonomic constraint on the platform. Next, in part (b) of the figure, the end-effector (now the end of the drilling tool) moves along the segment of the trajectory labeled B. This involves controlling the orientation of the drill to maintain a fixed drill-bit axis. This motion is repeated for a second hole, and in part (c) of the figure the manipulator moved to put down the drill. Finally, in part (d) the drill has been released, triggering another Jacobian re-computation, and the platform moves off to the left. The non-holonomic constraint of the platform is illustrated by the "cusp" motion typical of car-like robot maneuvers.

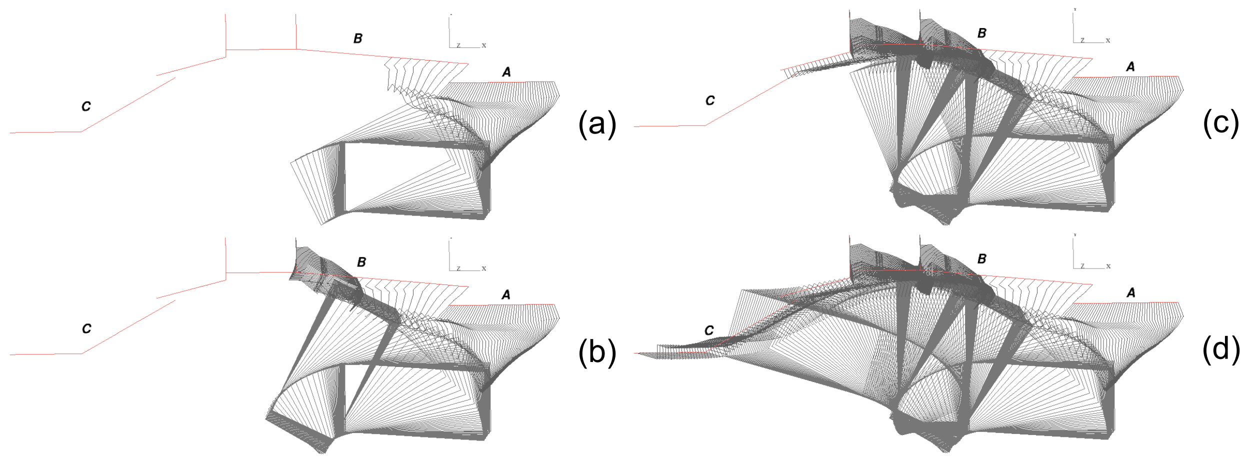

Fig. 1: Simulated trajectory for hole-drilling task with tool change and constraints.

A second example of the utility of the automatic generation of the kinematic equations is size reduction for DOE D&D tasks. The manipulator of choice for DOE operations is the Schilling Titan II and Titan III manipulators due to their compact size and high payload capacity. Many present and future D&D tasks consist of reducing metal components in size. Traditionally, this task calls for reciprocating saws, band saws, and plasma torches. For flat components, the kinematics of the Titan series manipulator is sufficient for making relatively large cuts. However, during preliminary attempts at cutting angled components (e.g., I-beams, box beams, angle iron), it was quickly realized that the kinematics of the manipulators severely limited such operations. The Titan manipulator's off-center wrist required very large displacements of the arm when the task required orientation changes that exceeded 45 degrees. In the example of cutting angle iron (shown in Fig. 2), it was very difficult to identify a position and orientation of the beam, with respect to the manipulator, that would enable a seamless cut from one side of the angle iron to the other. While the Titan series manipulators have six degrees of freedom, the actual workspace that enables arbitrarily orienting the end-effector at ±45° with respect to its base is severely limited. However, by including additional degrees of freedom to the tool, as shown in Fig. 2, the manipulator's workspace is dramatically expanded and easily enables tasks such as cutting angled beams as shown below. The ability to automatically generate the inverse kinematics simplifies the process of path planning and control of the combined manipulator and smart tool.

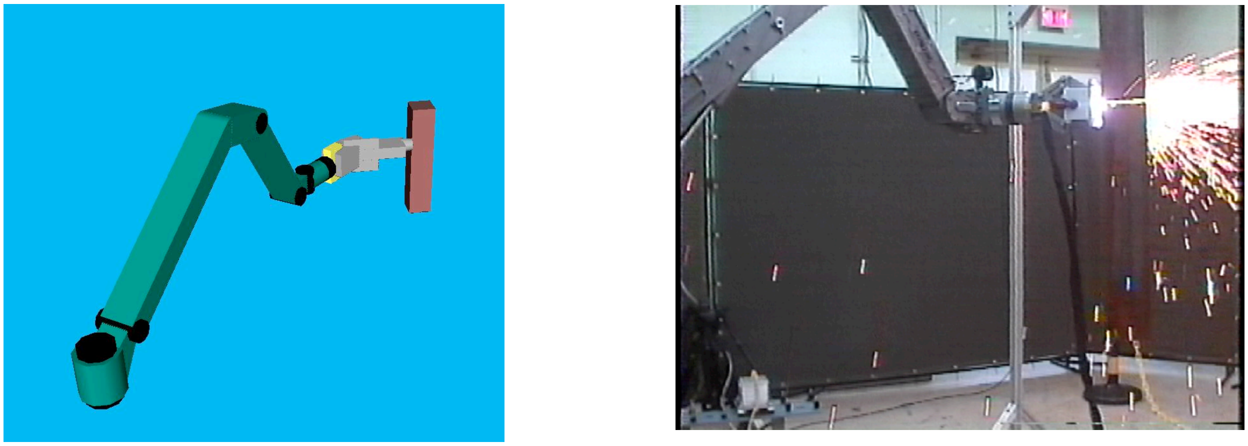

Fig. 2: Titan II with torch tool, during an otherwise impossible trajectory.

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References

1. F. G. Pin and D. L. Jung, "Robot Motion Planning with Time-Varying Constraints Using the Full Space Parameterization (FSP) Approach," in review, *IEEE Trans. Robotics and Automation*.

2. F. G. Pin et al., "A New Solution Method for the Inverse Kinematic Joint Velocity Calculations of Redundant Manipulators," *Proceedings of the IEEE International Conference on Robotics and Automation*, 1994, pp. 96–102.

3. F. G. Pin, K. A. Morgansen, F. A. Tulloch, C. J. Hacker and K. B. Gower, "Motion Planning for Mobile Manipulators with a Non-Holonomic Constraint using the FSP (Full Space Parameterization) Method," *Journal of Robotic Systems* **13**(11), 723–736, (1996).

4. F. G. Pin and F. A. Tulloch, "Resolving Kinematic Redundancy with Constraints Using the FSP (Full Space Parameterization) Approach," *Proceedings of the IEEE International Conference on Robotics and Automation*, 1996, pp. 468–473.

5. K. N. Fisher and D. L. Jung, "JFKengine: A Jacobian and Forward Kinematics Generator," ORNL/TM-2002/230, Oak Ridge National Laboratory, Oak Ridge, Tenn., March 2003.

6. F. G. Pin, K. N. Fisher and D. L. Jung, "Automated Generation of the Forward Kinematics and Jacobian Equations for Modular and Re-configurable Robots," in review, *IEEE Trans. Robotics and Automation.*