CINEGEN: A RAPID PROTOTYPING TOOL FOR ROBOT MANIPULATORS

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ABSTRACT

CINEGEN is a Virtual Reality based system for the rapid design, prototyping and simulation of robot manipulators. With CINEGEN, users provide a text description of a manipulator and a numerical algorithm automatically computes the inverse kinematics. This algorithm is capable of handling serial, parallel and hybrid manipulator structures.

Using CINEGEN, the user can directly interact with a graphical manipulator: he can define tasks in Cartesian space and the program generates real time inverse kinematics to show the behaviour of the robot. Graphical information representing internal parameters (speeds, torques, accelerations) help the user to understand robot problems and optimise the design. Additionally, to enhance the intuitive interaction with the software interface, a new type of 3D mechanical device with force feedback is being developed.

This interface is currently being used by EPFL-ISR (Lausanne, Switzerland) and NASA Ames (Moffet Field, California) to control several manipulators as well as to prototype new designs.

INTRODUCTION

This paper describes an innovative user interface for high-level control of robot manipulators. This interface is based on Virtual Reality which allows the user to interact in an intuitive way with the robot. The core of the program is a generic kinematic generator which provides real time kinematics of any robot manipulator.

We first present the method to achieve real time simulation of articulated structures. Then we show what functionality the interface provides to the user. We conclude by presenting some examples to illustrate the results already obtained.

Background

The Micro-Engineering Department (Institut de Systèmes Robotiques, ISR) of the Swiss Federal Institute of Technology (EPFL) is involved in robotic design and development, with a special focus on industrial applications. Our prior experiences with industrial partners showed that classical methods for robotic systems programming (off-line as well as on-line) lack user-friendliness and performance. Thus, since 1990 we have been developing Virtual Reality (VR) interfaces to simplify robot task planning, supervision and control [1][2].

In addition, our collaboration with the Intelligent Mechanisms Group (IMG) of the NASA Ames Research Centre (developers of the Virtual Environment Vehicle Interface [3] [4], a user interface to operate science exploration robots) has shown that a tool to generate rapidly VR interfaces for new robot manipulators would provide great benefits.

This need for a new tool (for both the ISR and the IMG) to build interfaces and to control any type of robot arm led to the development of CINEGEN.

Design

The goal of CINEGEN is to furnish a general tool to build, study and control robot manipulators. The requirements for such a tool are of two types:

- a program which can handle the kinematics of any robot structure in real time.
- an intuitive user interface to allow both novices as well as experts to easily manipulate robots in the virtual environment.

In CINEGEN a robot is seen as a set of ordered links and constraints. These constraints can be relations between two links or between a link and external input device. The addition or removal of constraints allows either forward or inverse kinematics of any kind of structure (serial or parallel) to be performed.

A robot is defined with a text file containing all the geometric properties of links and the relationships between links forming the desired structure. CINEGEN parses this file and builds the corresponding robot in a graphical Virtual World. Then the calculations to solve all the constraints are performed continuously. This allows the user to move the robot using 3D input devices, with either direct or inverse kinematics. Fig. 1 shows the global structure of CINEGEN.

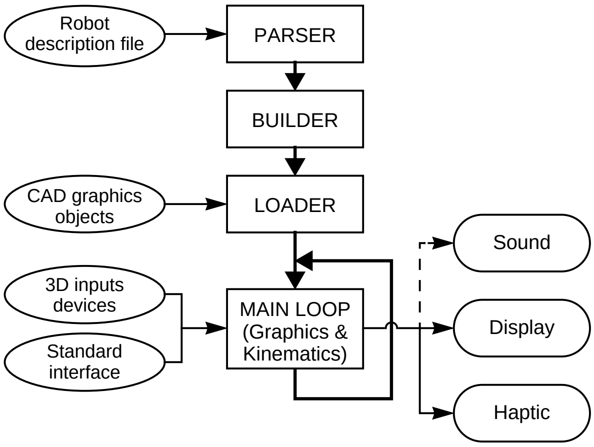


FIGURE 1: Components of the program

METHOD

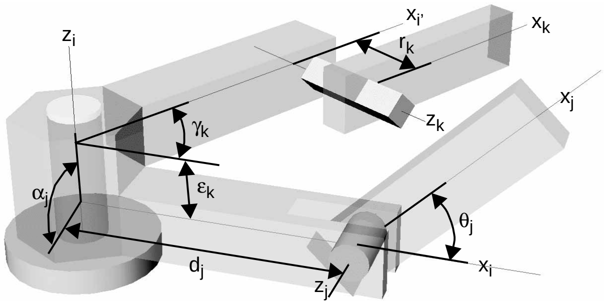
In order to rapidly build and study manipulators, we first need a flexible, easy to use method to describe general structures. Then given a description we need to be able to compute manipulator kinematics while considering appropriate constraints.

Robot description

The first requirement is mathematical description of the spatial transformations between each joint. Several symbolic notation for mechanisms are well-known. The classic Denavit-Hartenberg (D-H) [5] notation, or its Paul [6] version, are still widely used due to their usefulness and clarity. But they both lead to ambiguities for kinematic chains with more than a single branch. The Sheth-Uicker (S-U) [7] method extends the D-H notation for multiple loop kinematic chains in the general case, but is much more complicated to use due to the number of additional coordinate systems (two per link for a simple serial chain).

For CINEGEN we have chosen a third method (illustrated in Fig. 2) introduced by Kleinfinger [8][9], which presents the following advantages:

- Usable for all serial, treelike or closed loop kinematic chains.
- As simple as the D-H notation in the serial case.



Construction rules:
Z_i = axis of joint i
X_i = axis of common perp. at Z_i & Z_{i+1}

Joint variables for link i:
prismatic joint: r_i
rotational joint: θ_i

Fixed parameters for link i:
d_i & α_i

Parameters for joint fork:
ε & γ

FIGURE 2: Kleinfinger notations

- Fewer parameters than the S-U notation in complex cases.

RAFF file

In CINEGEN, manipulators are described in a text based *Robot Arm File Format* (RAFF). Each manipulator is defined as a tree structure from the base up to the end effector. For robots with kinematics loops, the desired chain is closed using a constraint between two branches of the tree.

```
RAFF MiniDelta

robot r1 {

   // here’s the base of robot
   base { filename { “plateform.dxf” } }
   ...

   link 2 {  // first link of the robot
      parameters {
         theta  0.0    // in degrees
         r      0.0    // in mm
         d      1500.0 // in mm
         alpha  90.0   // in degrees
      }
      type 2 // type of joint 2=revolute
      pred 1 // predecessor
      range { -60.0 60.0 }
      filename { “bras.nff” }
   }

   // define a closed loop constraint
   constraint {
      link 5   // this two links must
      link 11  // be connected
   }
   ...

}  // end of robot definition
```

FIGURE 3: Part of a RAFF file

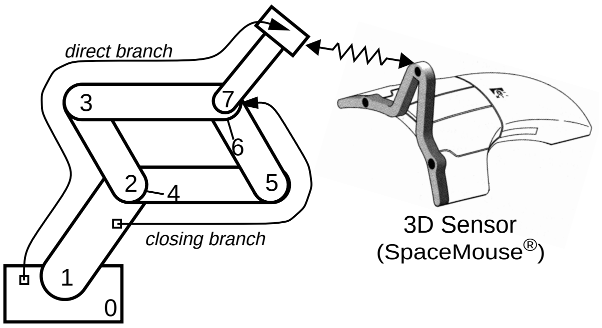
The same type of constraint is used to perform inverse kinematics: a constraint is set between a link and a list of potential input devices. Then when the constraint is active, the link must follow the movements defined by the user. The Fig. 3 shows a portion of a typical RAFF file. The RAFF file is a crucial part of the CINEGEN tool, since it is the link between the user's knowledge and the algorithms used to generate the virtual environment.

Solver

For CINEGEN, we have chosen to use a numerical method to perform the kinematic calculations because:

- real time solution is required.
- must operate for any robot without recompilation of the program.
- only one solution is necessary (the closest to the current position).
- high precision is not needed (does not replace the controller of the robot).

CINEGEN uses an extended Jacobian to represent the constraints in a kinematic chain. Then a numerical inversion using Singular Value Decomposition (SVD) [10][11] is applied to obtain the robot modification regarding the user inputs. Fig. 4 shows an example of the construction of the extended Jacobian for a planar manipulator with seven joints and one loop.



$$J' = \begin{bmatrix} d_{x1} & d_{x2} & d_{x3} & 0 & 0 & 0 & d_{x7} \\ d_{x1} & d_{x2} & d_{x3} & 0 & 0 & 0 & d_{x7} \\ d_{\alpha 1} & d_{\alpha 2} & d_{\alpha 3} & 0 & 0 & 0 & d_{\alpha 7} \\ 0 & -d_{x2} & -d_{x3} & d_{x4} & d_{x5} & d_{x6} & 0 \\ 0 & -d_{x2} & -d_{x3} & d_{x4} & d_{x5} & d_{x6} & 0 \\ 0 & -d_{\alpha 2} & -d_{\alpha 3} & d_{\alpha 4} & d_{\alpha 5} & d_{\alpha 6} & 0 \end{bmatrix} \begin{array}{l} \left.\vphantom{\begin{array}{c} d \\ d \\ d \end{array}}\right] \textit{end-effector constraint (user input)} \\ \left.\vphantom{\begin{array}{c} d \\ d \\ d \end{array}}\right] \textit{closed-loop constraint (robot structure)} \end{array}$$

FIGURE 4: Construction of the extended Jacobian

The number of robot's joints define the number of rows of the extended Jacobian J'. The number of columns of the Jacobian equals the number of degrees of freedom in the user space (three in the plane, six in the 3D space) multiplied by the number of constraints.

At any time (1) represents the state of the robot:

$$\begin{bmatrix} \dot{x} \\ 0 \end{bmatrix} = J' \cdot \begin{bmatrix} \dot{\theta} \end{bmatrix} \quad (1) \qquad \begin{bmatrix} \dot{\theta} \end{bmatrix} = J'^{\dagger} \cdot \begin{bmatrix} \dot{x} \\ \varepsilon \end{bmatrix} \quad (2)$$

This means that the extended Jacobian matrix multiplied by the joint velocities vector $\dot{\theta}$ should equal the vector composed of the Cartesian velocities $\dot{x}$ and a null vector. This null vector characterizes that the contribution of each sub-chains of the loop should be the same.

Taking the pseudo inverse $J'^{\dagger}$ of the extended Jacobian, leads to (2) which solves all the robot constraints (ε is an error vector to help the algorithm to "re-close" the loop when numerical problems appear). Thus we have the inverse kinematics of the robot with $\dot{\theta}$ regarding both the user inputs and the internal constraints. When only direct kinematics is required, only the last rows of the extended Jacobian are solved to preserve the coherence of the structure. Of course for serial manipulators, no Jacobian is required to solve the direct kinematics.

Given a representation of the robot as an oriented graph, the extended Jacobian can be easily rebuilt when the constraints change. This allows the user to switch from forward to inverse kinematics dynamically whatever the type of the robot may be.

INTERFACE

Besides the numerical algorithms for kinematic calculations, the usefulness of CINEGEN comes from the interface and how the user can directly interact with robots.

Inputs

The CINEGEN interface is based on Virtual Reality and uses 3D sensors to allow users to give inputs to the robots. At present, two devices are primarily used for CINEGEN having both their advantages and drawbacks. The Magellan® from Logitech acts like a joystick, and gives information about the three directions of translations and the three rotations. The SpaceMouse®, shown in Fig. 4, is an absolute sensor which one can move and rotate in the 3D space.

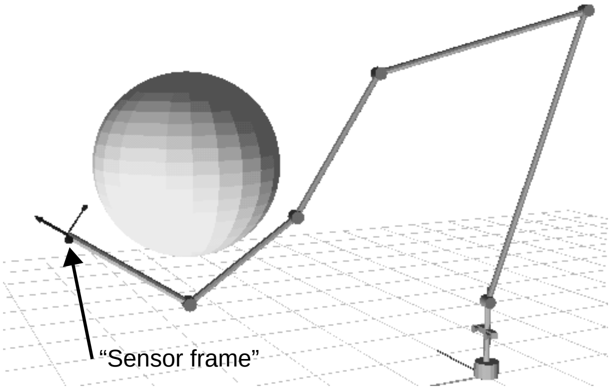
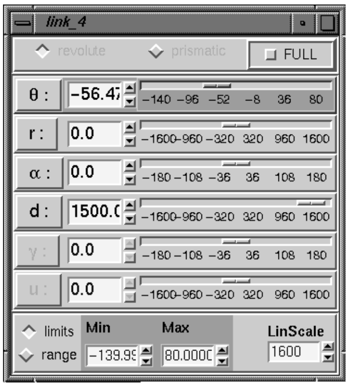


FIGURE 5: A highly redundant "virtual robot" showing a frame where the sensor is attached

The user decides on which part of the robot the 3D sensor acts (see Fig. 5), and is able to move this part in the 3D space. The fully structure tries to follow the inputs given by this sensor, keeping all the other constraints respected. To perform inverse kinematics, the user does not have to care about the number of degrees of freedom (d.o.f.) the current robot has: the algorithm optimise the trajectory regarding the robot capabilities. In the case of an under-actuated robot, the user will not be able to move the robot in some configurations. For a redundant robot, the joint speeds are be minimized, but other algorithms can be easily implemented.

With the CINEGEN interface one can also dynamically change any parameters of the robot structure using the dialogue box shown in Fig. 6.

This dialogue box uses redundant controls to give maximum flexibility to the user. With the same dialogue box, one can also perform forward kinematics of the robot by in varying the highlighted parameter. This allows the user to directly see the influence of a parameter on the structure and to find the correct Kleinfinger parameters for a complex link.



θ : -56.47
r : 0.0
α : 0.0
d : 1500.0
γ : 0.0
u : 0.0
Min -139.99
Max 80.0000
LinScale 1600

FIGURE 6: Dialogue box to change the link's Kleinfinger parameters

Outputs

Of course, the main output is a graphic display of the scene on a screen. The user can at any time choose the best point of view of the scene containing the representation of the robot as other elements of the world. The display can be done in a single window, in multiple windows with different views, or in a stereoscopic mode[1]. In stereo mode the user can really interpret the robot's behaviour in the virtual world.

The purpose of the virtual world, however, is to go further than just presenting reality to the user: we can add 3D graphic information representing things the user cannot see normally. For example, we can show internal robot parameters such as joint speed (see Fig. 7) or acceleration, the load on a link, the overheating of a ball bearing, or external measures (e.g. distance to an obstacle). Using appropriate graphical representations (changing form or size of an additional object, colour or texture of a link), one can "attach" the information about one parameter to its associated mechanical part.

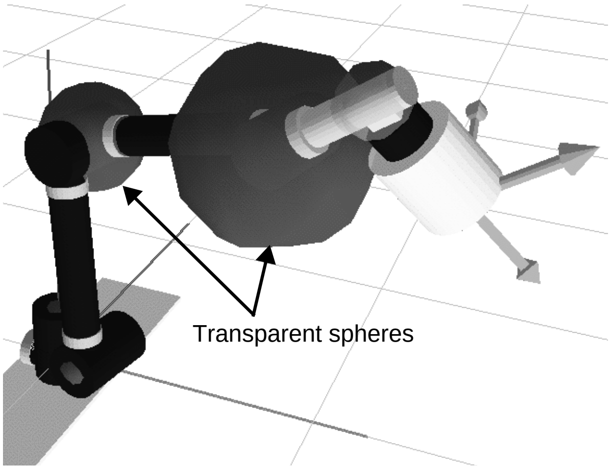


FIGURE 7: A 5 d.o.f. manipulator with transparent spheres representing joint speeds

Haptic

To enhance the intuitive control of robots and improve the feeling of the mechanical structure, we are developing a new type of input device with force feedback. This device mixes the 6 d.o.f input capabilities with haptic output.

The key point of this device is to decouple translations and rotations:

- The translational structure is based on the DELTA robot concept developed at the ISR: three kinematic chains passively constrain a moving plateforme to be parallel to a fixed reference. This structure operates as an absolute sensor: the user moves his hand in 3D space to where he wants the robot to go.
- Rotations are achieved by a small "joystick like" device attached to the moving plateforme. This structure has 3 rotational d.o.f. around a fixed point. This part of the device is only incremental: the rotational speed of an object in the virtual world is proportional to the angle the user turns the joystick.

This design efficiently exploits the human "arm+hand" capability and is suitable to control any robot manipulator through a 6 d.o.f. space: it is not limited by the kinematic structure of the manipulator being operated.

Fig. 8 shows our new input device. It is actuated by six DC motor which generate translational forces on the moving plateforme, and give a variable resistance on the rotational joystick. This enables the user to "feel" the simulated robot: he can sense forces caused by collision with objects, perceive actuator load or feel when the robot reaches a singularity.

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[1] The stereo display is created by alternatly rendering a image computed from a left "camera" and a right "camera", synchronised with stereo glasses allowing each eye of the user to see the corresponding image.

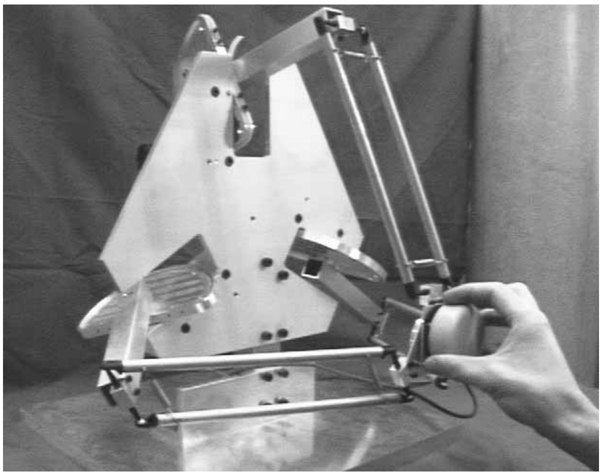

FIGURE 8: The haptic interface developed for robot manipulators control

RESULTS

CINEGEN has already been used to build several virtual manipulators. Some of these prototypes have real counterparts, while other are completely new designs. We have successfully simulated a wide range of manipulators in the three groups of kinematic chains: serial, fully parallel and hybrid.

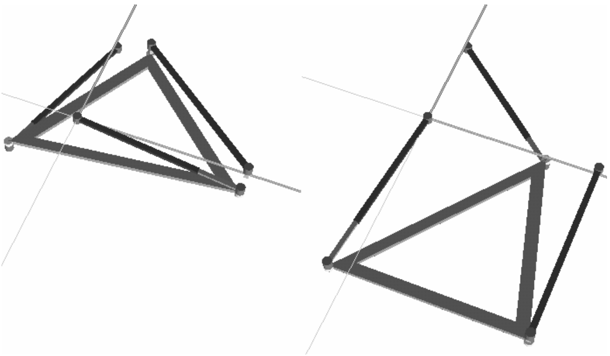

FIGURE 9: Two configurations (same actuators values) of a planar 3 d.of. parallel manipulator

We have found that the time to build a new structure is dramatically reduced due to the simplicity of the RAFF file, the possibility to run a new simulation without recompiling anything, and the dynamic tools provided. In thirty minutes for a simple structure to two hours for a complicated parallel structure[1], we are able to create a virtual environment to study the new design. The interactive 3D representation allows the user to adapt easily the robot movement (in the case of an existing robot) or the robot structure (in the case of a new design) to the desired task. You can also record the planning of a whole task in order to send the corresponding commands to a real robot. The choice for the user to perform either direct or inverse kinematics from the same RAFF file is also an important time savings. In addition, planar manipulators can also be easily simulated, without any modification to the program or specifying it in the RAFF file. Fig. 9 shows a case study of a planar Stewart plateforme which is able to change its configuration without passing through a singularity [12].

Finally, it should be noted that having a real-time simulator is essential for the intuitive use of the interface. The current implementation[2] provide a frame rate above 30Hz for all the manipulators we have simulated. In addition the software is written in modular, object-oriented way, which allows an easy implementation of new modules, or interaction with other programs. For example, CINGEN has already been interfaced with the new visualisation tool (called MainViz) by the Intelligent Mechanisms Group (NASA Ames). It allows different users to see manipulators build with CINEGEN across the network and share the virutals worlds.

CONCLUSION

CINEGEN is an innovative approach to real time user-robot interaction. It provides easy access to robot description and simulation and a friendly interface. The use of CINEGEN by different users and different simulations have confirmed its capabiliy for rapid design and study of new manipulator structures.

The combination of CINEGEN with the new haptic interface provides a complete environment suitable for design and conception but also for performing teleoperation in an effective manner.

Future work will focus on integrating high order joint pairs (universal, spherical, etc.) in the robot model to speed up the simulation of large structures. Improving the Jacobian inversion for complex cases, and adding algorithms for better singularity management is also in progress.

ACKNOWLEDGMENTS

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