A robot interface using virtual reality and automatic kinematics generator

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***Abstract* - This paper describes an innovative user interface for high-level control of robot manipulators. The interface uses virtual reality to provide the user with an interactive 3D graphical representation of the manipulator.**
The interface is designed to give a novice user an intuitive tool to control any kind of mechanical structure (serial, parallel or hybrid) without requiring any programming skill. The user simply describes the geometric properties of the manipulator and then inverse kinematics are automatically calculated in real time, in order to move any part of the robot through 3D input devices. The interface is also designed to provide the user decision capabilities when problems, like singularities, are encountered. Lastly, to enhance the intuitive use of the interface, a new mechanical input device with force-feedback is being developed.
This interface is currently in use at EPFL-ISR (Lausanne, Switzerland) and NASA-Ames (Moffett Field, California) to control a variety of industrial and research manipulators as well as to study new designs.

I. INTRODUCTION

This paper describes a new kind of robot interface which uses Virtual Reality and allows the manipulation of any type of robot structure, using an automatic kinematic generator. We briefly explain the principles of the program (more details can be found in [1]) and then describe what this program offers to the user. We conclude by presenting some results already obtained.

A. 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 experiences with industrial partners showed that classical methods for robotic systems programming (off-line as well as on-line) lack user-friendless and performance. This is why, since 1990 we have been developing Virtual Reality (VR) interfaces to simplify robot task planification, supervision and control [2].
In addition, our collaboration with the Intelligent Mechanisms Group (IMG) of the NASA Ames Research Center (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 robots arm 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 leads to the CINEGEN project.

B. Goal

The goal of the CINEGEN project is to provide novice users with an intuitive tool for designing, studying and controlling robot manipulators (serial, parallel or hybrid) without the need for complex programming.
This is achieved with a Virtual Reality based interface in which the user generates, visualises and manipulates robot manipulator arms. The kernel of the program is a general kinematic generator which can calculate in real time the inverse kinematics of any mechanical structure.
The description of the geometric properties of the robot is specified in a simple text file. This file is then read by the program in order to generate a virtual world containing the corresponding “movable” robots. Inside this VR interface, the user can interact with the robot in an intuitive way. This means that the operator can pick any part of the robot and move it (in the general sense: translations and rotations), using 3D sensors, wherever he wants, as easily as a “drag and drop” program. Thus, trajectories can be defined, optimised and stored easily. The interface also provides the user with information about current parameters of the robot to help the user in trajectory decision making. The main relations existing in the CINEGEN project are shown in Fig. 1.

C. Method

To achieve the desired goal, we have to consider first how to describe a robot. Then since we may want to move any part of

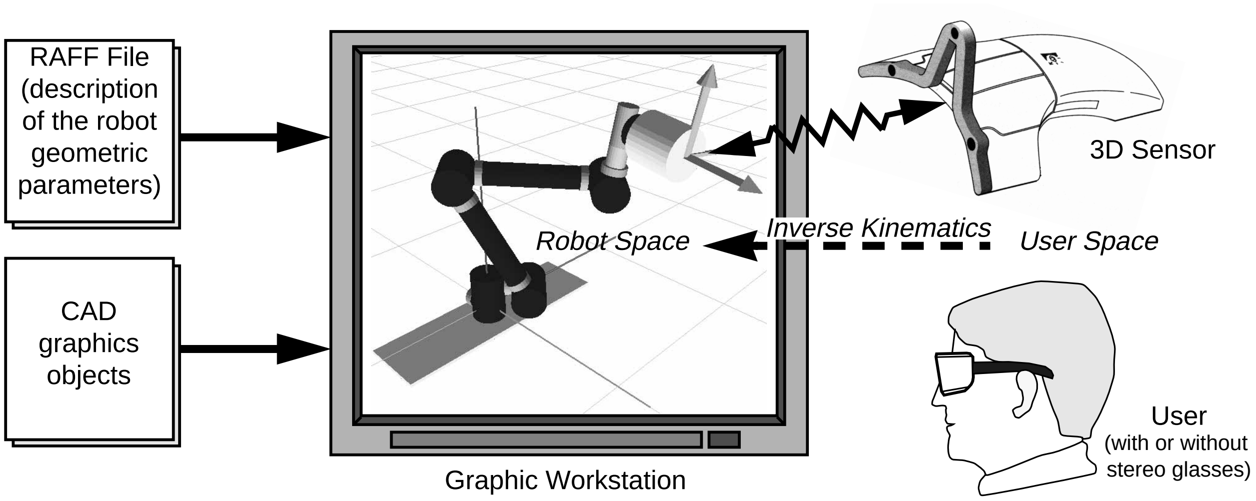

Fig. 1. Overview of CINEGEN user interface.

the robot (usually the end-effector) we need a method to solve the inverse kinematics of the robot. Finally, we have to display the real time simulation on a graphic screen or similar device.

1) Inputs

The first requirement is to find a notation for describing the robot arm, suitable for any type of structures: serial, parallel or hybrid. We have chosen a method described by Kleinfinger [5][6] which uses a maximum of six parameters for each link. For our purpose, this notation is more appropriate than other well known conventions like Denavit-Hartenberg (D-H) [7] or Sheth-Uiker (S-U) [8] due to the following:
- usable for serial, treelike or closed loop kinematic chains;
- as simple as the D-H notation in the serial case;
- fewer parameters than the S-U notation in complex cases.

With the Kleinfinger notation, structures are described as a tree of links. For serial arms, the tree contains only a single branch, while for multiple end-effector arms, it has several ones. Closed loops mechanisms are also represented as trees: each loop is “broken” at a user-defined joint and new constraints are added to re-close this loop during simulation.

We describe robots (using Kleinfinger notation and tree structure) in a text based Robot Arm File Format (RAFF) by specifying a series of joints (revolute or prismatic), their parameters and their hierarchy. The RAFF file is a crucial part of the general kinematic simulator, since it is the link between the user knowledge and the computer algorithms used to generate the virtual environment. Thus, a RAFF file format must be designed to be easily understood from both the user and the visualization program, as well as to be automatically generated from external software. This RAFF file contains also the description of the sensors used to control the robot, i.e., the port on which they are connected, their type and how they can interact with the robot.

2) Solver

Different methods exist to solve the problem of robot inverse kinematics, but the general case remains a challenge. In the CINEGEN project, the fundamental requirement is real-time inverse kinematics of any kind of robot manipulator. However, in the context of the VR interface, we can simplify the problem: the robot configuration is known at the beginning of the process, and then at any time during the simulation. Thus, there is a continuity in the robot position which eliminates the need to find all acceptable configurations. This allows us to use a numerical inversion of the Jacobian to find the inverse kinematic solution.

Our program builds an “augmented-Jacobian” at each simulation loop. The augmented-Jacobian is the concatenation of the Jacobian of each direct kinematic chain, to which we add a set of additional rows representing the closed loop constraints. Thanks to the internal representation (in the program) of the robot as a dynamic directed graph, the algorithm to build this augmented-Jacobian is straightforward.

Once the augmented-Jacobian is calculated, it is inverted using a singular value decomposition (SVD) [9]. The SVD allows us to invert non-square matrices, giving good “pseudo-inverse” matrices in term of minimization of chosen physical parameters. In addition it provides useful information about mathematical singularities, and gives “user level” control about how to treat such singularities.

3) Visualization

We have developed a real time graphic simulator which allows users to interact directly with robot models. The robot movements are calculated in real time from sensors inputs and the corresponding 3D graphic model is generated. The graphics model representing the robot consists of CAD components specified via the RAFF file. When the simulation is running, the user can move around in the virtual world and see the virtual robot from the best viewpoint. If the user gives an input on a sensor device linked to a part of the robot, he directly sees the corresponding behaviour of the entire robot structure. This allows direct interaction between the user and the virtual robot.

II. PROPOSED TOOLS

Since the CINEGEN project is intended to provide a complete intuitive interface for users to interact with robot manipulators, the use of adequate input devices is as important as good visualization tools.

A. Sensors[1]

It is possible to use conventional input devices, such as a standard mouse or a button box, to control the virtual robot. But a mouse is by nature a 2 degrees of freedom sensor. To control a 6 degrees of freedom manipulator it is necessary to use the mouse in conjunction with 2 or 3 buttons. Consequently, a standard mouse is only suitable for controlling very simple mechanisms, or for interacting with a conventional graphic interface (i.e. you use the mouse to “click” on buttons or graphics controls).

To provide the user with a better interface, CINEGEN uses real 3D sensors rather than standard input devices. A 3D sensor must allow displacements in the 3 axes of translation and in the 3 axes of rotation. Due to the development of the VR applications, many 3D input devices are now available on the market. It is possible to classify them in two groups (based on their operating mode):
- absolute devices like the FastTrack from Polhemus or the 3D ultrasonic Mouse from Logitech. The user moves these sensors in the 3D-space to the desired location (position and orientation). These sensors are very intuitive as the user moves his hand to the actual point he wants to reach. But in the case of controlling a robot manipulator, the rotations are more difficult to produce due the limited range of the human wrist (either you get a smaller range than the robot you want to control, or you loose precision by scaling the movement);
- incremental devices like the SpaceBall from Silicon Graphics or Magellan from Logitech. These sensors act like a joystick with more degrees of freedom: the controlled object moves in the direction you are pushing your sensor, with a speed proportional to the force (or the shifting) you give to the sensor. Reaching a point is more like flying to it, and giving a permanent torque (or a small rotation) to the sensor allows one to rotate as much as desired.

These two types of 3D sensors are currently used to control the virtual robot in the CINEGEN simulation. To enhance the intuitive control of robots and improve the feeling of the mechanical structure, a new type of input device with force

1. The term “sensor” is used for any input device through which the user can give orders to a program in a general sense: a sensor can be a mouse or a widget containing scrollbars. In addition, the sensor is implicitly connected to a driver which generates readable data by the program.

feedback is being developed. This device is designed to have 6 degrees of freedom and to take advantage of the human “arm+hand” capability. Specifically, the device decouples translation and rotation inputs: it can only be moved along the 3 translation axes. Rotations are achieved by a small incremental joystick. The translational structure is based on the DELTA robot concept developed at the ISR: three kinematic chains passively constrain a moving platform to be parallel to a fixed reference. The rotational structure is designed as a 3 degrees of freedom device, supported by the moving platform, and preconstrained in the three axes of rotation. Thus, this novel device not only combines absolute translation with incremental rotation, but also accommodate up to 6 degrees of freedom force feedback. This enables the user to “feel” the simulated robot: he can sense forces caused by objects collision, perceive actuator load or feel when the robot reaches a singularity.

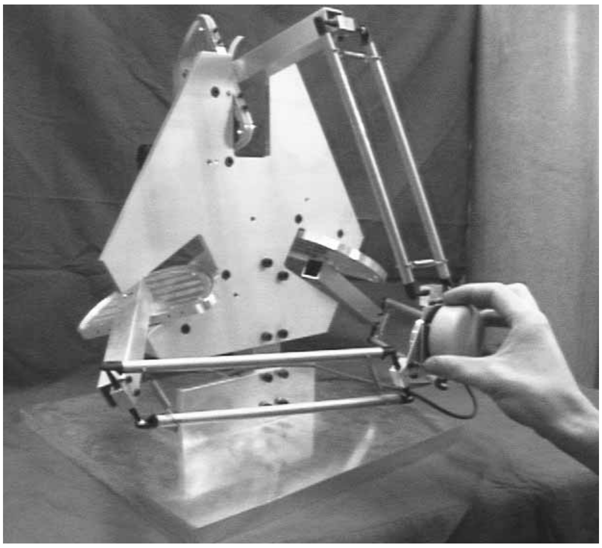

Fig. 2. The new input device prototype with force feedback developed for the CINEGEN user interface.

B. Interaction and visualization

The generated virtual world enables the user to continuously interact with a graphical 3D representation of the robot, to observe its reaction to inputs, and to understand its movement behaviour and interaction with the others objects/robots in the scene (multiple robot simulation and multiple sensor usage in the same scene is allowed by the grammar of the RAFF file and the program engine). In addition, CINEGEN includes several tools to help the user during the stage of developing a new robot structure, and then analyse the new simulated structure.

To assist the user in building simulations, we have developed an “automatic link construction” feature. When the user does not want to draw CAD objects representing links and joints of the robot, he can replace the name of the corresponding graphic file (in the RAFF file) with the keyword “auto”. In this case, the program automatically builds a set of graphic objects to represent the corresponding joint-link, based on the Kleinfinger parameters. This reduces drastically the time to design a new structure, since the user does not care about drafting until he has found good parameters. Furthermore, using automatic link construction, and the real time numerical solver, we allow dynamic changing of link parameters. This means that the user can change any link parameter (for example extend it) during the simulation. For this purpose we have created a special dialog box to adjust the parameters of a link. This allows the user to see directly the influence of a parameter on the structure and to find the good Kleinfinger values for a complex link.

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 robot internal parameters such as joint speeds or accelerations, the load on a link, the overheating of a ball bearing, or external measures (e.g. distance to an obstacle). Using adequate representations (changing form or size of an additional object, colour or texture of a link), you can “attach” the information about one parameter to its associated mechanical part. Thus the user can obtain a direct feeling (visual and haptic) about the behaviour of the system and the relations between the different parts.

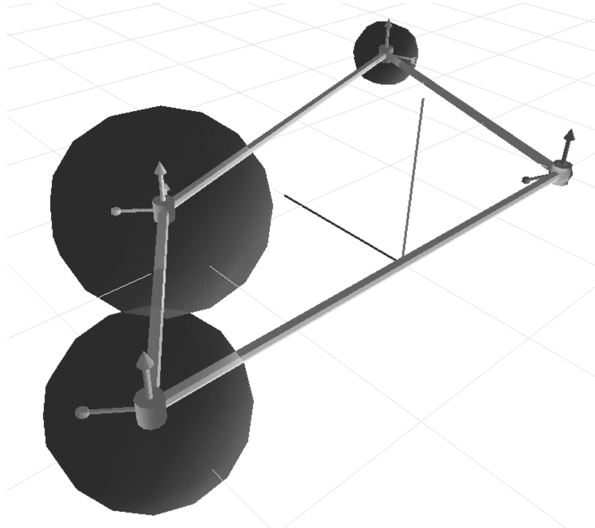

Fig. 3. A Four-Bar linkage with transparent spheres representing joint speeds.

Lastly, the CINEGEN program is a tool to operate robots (at the task level) with a philosophy of “user level control”, i.e. the user as a part of the control loop. The robot tasks are clearly defined by the user. For example, the definition of a trajectory in the 3D space is specified with a user’s hand movement, rather than being calculated automatically (e.g. with potential field). The program provides tools for elementary tasks, such as grasping an object (the user selects an object in the virtual world, and the program generates the small trajectory to grasp it), but leaves the high level decisions to the user. This method allows to incorporate the user intelligence inside the control loop. For example, consider the case of a robotic arm reaching a singularity. One method is to use an automatic algorithm to avoid this singularity (like the “damped least square” method). Our approach is different: we show the user that the robot is reaching a singularity, drawing a “phantom” robot in this configuration, and ask the user on which side of this singularity the robot should go.

III. RESULTS

Several virtual manipulators were built with CINEGEN, some representing their real counterpart robot, and others as a design exercise to study new manipulators. We have tested manipulators belonging to the three groups of kinematic structures: serial, parallel and hybrid.

The current implementation gives also the expected performances about real-time simulation as show the table 1.

Table 1: Characteristics and performance measurement for several simulated robots.

	Simple serial robot	**Hybrid manipulator**	**Parallel structure**	**Redundant arm**
Number of Joints	5	9	18	7
Number of Loops	0	1	3	0
Frame Rate during simulation*	45Hz	45Hz	30Hz	45Hz
Time of development**	45min - 1h	45 min - 1h	1h - 2h	10min - 20min
Remark	existing robot	same structure as an industrial robot	design of a new robot structure	imaginary robot, just for tests

* On a Silicon Graphics High Impact 250MHz R4400 processor. The graphics of all robots were simplified to obtain a 60Hz frame rate with the inverse kinematic algorithm disabled. (Frame rates are discrete).
** For a RAFF trained user. Including the search of Kleinfinger parameters and common mistakes. Without the time to draft the CAD files.

In addition, the RAFF file has proven to support rapid development of new structures. This has enabled rapid prototyping of interfaces for controlling existing robot arms, as well as speeding up the research of new designs. With the help of the VR interface, the user can study if a specific structure is well adapted to the task, and adjust the structure parameters to optimise the task. We have found that the use of a VR interface to simulate robots drastically improves the “feeling” of the robot. In particular, the interface allows us to understand the behaviour of an existing robot, and to find why a new designed structure does not work as expected. For example, during preliminary development of a new parallel robot structure at ISR, the use of CINEGEN revealed that the orientation of some universal joints were wrong (on parallel structures, this kind of problem is difficult to put in evidence).

IV. CONCLUSION

The CINEGEN project demonstrates that it is possible to build a real time simulator, using appropriate methods, for general robot structures. In addition, using a virtual environment interface enables users to have direct interaction with simulated robots. This allows the user to “feel” the simulated structure, and to act directly in the control loop.

It should be noted that the program we have developed is not intended to compete with mechanical modelling software (which allows analysis of kinematics, dynamics, etc.), but rather is a supplementary tool for rapid robot prototyping and control.

Future work will focus on improving the Jacobian matrix inversion algorithms for complex cases, and on integrating higher order joint pairs (universal, spherical, etc.) in the robot model to speed up simulation of large structures.

The CINEGEN current implementation uses an open architecture which easily allows new “plug-in” modules, and is available for distribution to interested research groups.

V. ACKNOWLEDGMENTS

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