

## ROBOSIM: AN INTELLIGENT SIMULATOR FOR ROBOTIC SYSTEMS

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### ABSTRACT

The purpose of this paper is to present an update of an intelligent robotics simulator package, ROBOSIM, first introduced at Technology 2000 in 1990. ROBOSIM is used for three-dimensional geometrical modeling of robot manipulators and various objects in their workspace, and for the simulation of action sequences performed by the manipulators. Geometric modeling of robot manipulators has an expanding area of interest because it can aid the design and usage of robots in a number of ways, including: design and testing of manipulators, robot action planning, on-line control of robot manipulators, telerobotic user interface, and training and education. NASA developed ROBOSIM between 1985-88 to facilitate the development of robotics, and used the package to develop robotics for welding, coating, and space operations. ROBOSIM has been further developed for academic use by its co-developer Vanderbilt University, and has been used in both classroom and laboratory environments for teaching complex robotic concepts. Plans are being formulated to make ROBOSIM available to all U.S. engineering/engineering technology schools (over three hundred total with an estimated 10,000+ users per year).

### INTRODUCTION

In the development of advanced robotic systems concepts for use in space and in manufacturing processes, researchers at NASA and elsewhere have traditionally verified their designs by means of expensive engineering prototype systems. This method, though effective, frequently required numerous re-design/fabrication cycles and a resulting high development cost. To reduce costs ROBOSIM, a graphics-based simulator for robotic systems, was developed to allow rapid prototyping of robotic systems, including robot manipulators, multi-axes positioners, other motion-controlled mechanisms, and objects and structures in the operating environment. The reduced costs obtainable with the graphical simulator allows experimentation with many design alternatives prior to implementation in hardware resulting in improved end-item designs.

Researchers at Vanderbilt University (co-developers of ROBOSIM) have further refined the simulation package to fully exploit its various capabilities in the teaching of courses on robotics, mechanisms, industrial control, and advanced automation at both the undergraduate and graduate levels. ROBOSIM provides the students with a graphical means of visualizing objects and their relationships in 3-dimensional space. The relationships between coordinate frames that have been translated and rotated relative to one another are immediately provided in the form of transformation matrices, and they may be displayed and viewed from different viewing positions. With the simulation system, students may actually graphically construct every manipulator they study in the classroom or in class assignments, and then they may operate the manipulator and use it to grasp, move, and release objects, and develop and test action plans for using the manipulators in practical settings. The costs of doing this with physical hardware would of course be quite prohibitive in terms of both dollars and time. ROBOSIM allows the students to be exposed to numerous robotic systems without any of the constraints placed on use of a specific physical laboratory robot. Furthermore, without any fear of injury the students may operate their manipulators at any hour from their personal computer performing tasks ranging from arc welding to robotic care of hospitalized patients, all within the confines of the interactive simulation environment provided by ROBOSIM!

With ROBOSIM, students construct a robot manipulator link by link and assign coordinate frames to the joints of each link. ROBOSIM automatically checks and validates the frame assignments and provides error messages stating the type of error and where it occurred if mistakes have been made. Once the links of the manipulator have been constructed, a single command automatically assembles the links into the complete manipulator. Any manipulator so constructed, regardless of its complexity and structure, may be immediately moved and controlled on a joint-basis with a single *drive* command specifying the manipulator by name and the joint values. Straight-line cartesian motion requires the inverse kinematics, which must be provided by the student, if not contained in the family of manipulators provided in the basic package. Once the inverse kinematic solution is linked into the program, the students may verify their solution by actually driving the manipulator based on their inverse kinematic control. With inverse kinematic control, higher-level commands may be issued to the robot, such as *move-to-grasp*, which commands the robot to move to grasp an object at a predefined position and orientation relative to the object. If obstacles are in the way, the command *find-path* may be issued instructing the robot to employ built-in artificial intelligence-based heuristics to search for a collision-free path.

In addition to the advanced features of collision detection and artificial intelligence-based collision avoidance routines, ROBOSIM includes other advanced features such as configuration management and composite objects. The latter, for example, permits the student to assemble parts into a composite assembly which can be operated on as a unit while preserving the separate accessibility of its components. This permits parts to be joined by welding or bolting, for example, and then transferred to other processing operations in the manufacturing process.

All of these capabilities of the graphical simulation approach to the study of robotics and automation provide the student with an almost limitless range of possibilities without the prohibitive cost of physical hardware, without the prohibited time required to use such hardware, and without the potential danger associated with the use of physical hardware.

There are over 300 engineering and engineering technology schools in the U.S. which currently offer courses in robotics, mechanisms, industrial control, and advanced automation. It is estimated that the number of students taking such courses exceeds 10,000 per year. Each of these students is being targeted as a potential user of ROBOSIM in a distribution plan that is being jointly formulated by NASA and Vanderbilt University. Additionally, while emphasis here has been placed on the use of ROBOSIM as a teaching tool in the academic community, virtually all of the features that make it useful there are equally applicable and useful to the industrial user. Plans are being formulated for distribution of ROBOSIM to the industrial community as well.

## TECHNICAL OVERVIEW OF ROBOSIM

The purpose of ROBOSIM, as it was originally conceived, was to provide a means of constructing and viewing three dimensional models of robot manipulators and various objects in their workspace, and simulating action sequences performed by the manipulators [1-4]. Geometrical modeling of robot manipulators is an expanding area of research because it can aid the design and usage of robots in a number of ways [5]:

- *Design and testing of manipulators:* The purpose of the modeling is to study different approaches to satisfy the design specifications of the manipulator.
- *Robot action planning:* The modeling environment is used to build a representation of the robot(s) and the objects in the workspace for creating and validating action plans by simulating the effect of these actions in the model space.
- *On-line control of robot manipulators:* The simulated action plans generated in the model space are transmitted (after validation) to the attached robot manipulators for execution.
- *Telerobotic user interface:* In applications where the operator of the robot has to be at a large distance from the workcell (nuclear facility, radioactive waste treatment, space, etc.) realistic graphical

simulations can be used for better interaction with the manipulator.

- *Training and education:* Robotic simulation packages provide an inexpensive and safe way to teach the theory and operation of robot manipulators.

### Design of Robot Manipulators: The ROBOSIM Modeling Environment

Similar to other solid modeling software tools, ROBOSIM models the three dimensional geometrical objects using lists of their bounding polygons. The ROBOSIM modeling language is used to specify complex geometric shapes which are used as manipulator links or as passive objects in models of robotic systems. All shapes are built from elementary geometric types like boxes, cylinders, cones, extruded polygons, etc. Translational, rotational and scaling geometrical transformations are used to combine these objects to form the desired shape. Link coordinate frames can also be added thus making it possible to specify the geometric transformations associated with a manipulator arm.

Once the ROBOSIM language interpreter finishes the processing of the code describing a solid shape, the resulting polygon list is converted into a named object (or robot link) in the robot simulator package's workspace. Thus the modeling of robot arms and objects and geometric scenarios is a two step process as follows:

- Modeling the geometric shapes, robot links, etc., which are used to build the scenario.
- Creating one or more named, distinguishable object instances of these shapes in the simulator's workspace.

These object instances can be individually manipulated upon, moved around, etc., from the interactive environment of the simulator, as described next.

### Operating the Models: The ROBOSIM Simulation Environment

The ROBOSIM package provides an interactive simulation environment where every command entered by the user is immediately executed and the results are displayed on a graphics screen. From this interactive environment users can change the simulation scenario and operate the robot manipulator models in the system. The commands available can be grouped as follows:

- *Environment configuration:* Besides the modeling services discussed above additional commands are available for the setting of global parameters like camera position, display mode, light sources, etc. The graphics display module of the simulator supports different display options like wire-frame, hidden line, solid filled and shaded graphics depending on the capabilities of the hardware platform.
- *Manipulator control:* There are commands available for moving the models of manipulator arms in various modes: joint interpolated, straight line, rotation about an arbitrary axis, etc. Manipulator coordinates can be specified both in joint and world coordinates. The simulator has a built-in iterative inverse kinematics algorithm, but the user can also specify an explicit inverse kinematics method for his or her manipulator if such a method is available. Additionally, the objects in the workspace can be grasped, moved, and released by the robots. If the scenario contains several manipulators these can be operated in parallel.
- *Status reporting:* Reports about different aspects of the simulator's operation (arm positions, collision situations, etc.) can be obtained by using one of the appropriate commands from this group.

The command language of the ROBOSIM simulation environment has been designed with two goals in mind: (1) to provide an interactive user interface, and (2) to be usable as the interface to a higher-level task planner program. In the second application the task planner and the robot simulator are typically interfaced using some kind

of pipe mechanism and the task planner outputs similar command sequences as entered by users in interactive applications. For this reason the command language has intentionally been kept simple.

### Advanced Features

Although the basic modeling and simulation environment described above perform quite satisfactorily as a robot modeling tool, ROBOSIM's capabilities were greatly enhanced with the completion of various extensions to the basic package. Some of these extensions use heuristic, rule-based programming techniques. The extensions include:

- *Composite objects:* The ROBOSIM simulation environment also supports the linking of separate objects into a so-called composite object which can be operated on as a unit while preserving the separate accessibility of its components. A good example of this is a drawer with various objects in the drawer. During the course of the simulation a manipulator may have to pull out the drawer (the drawer and its contents have to be treated as a unit) and then pick up a single object from the drawer (now a part of the composite object has to be accessed individually).
- *Configuration management:* When a manipulator arm is programmed using world coordinates it is typical to have several valid solutions (sets of joint coordinates) by which the manipulator can reach the desired position. For example, in the case of manipulators similar to the Unimation PUMA 560 robot this manifests in left or right handed and elbow up or elbow down configurations for the arm. ROBOSIM permits the user to choose any configuration and stay with it for the duration of the simulation. However, this approach is not optimal when the manipulator has to move distances comparable to the limits of its envelope. For such cases the simulator provides an automatic configuration selection mechanism which is based on a set of rule-based heuristics.
- *Collision detection:* ROBOSIM also provides a way to check for collisions during a simulation run. The collision detection is based on the detection of intersections of solid object (passive objects or manipulator links) bounding polygons. For efficiency reasons the simulator maintains a rectangular bounding box for every object and invokes the more complex polygon-based collision detection method only if the bounding boxes intersect.
- *Collision avoidance:* The simulator also provides a heuristic path planning algorithm which is capable of recovering from collision situations. The collision avoidance is based on heuristic rules describing actions to try in various collision situations. Some of these rules are generic, others are manipulator-specific. An example generic rule is the "minimal volume rule" which is usable for large displacements of the end effector. It specifies a path to reach the desired target which includes a midpoint where the arm is folded in a way which minimizes its reach. Users can attach other heuristic rules specific to their manipulator models.
- *Interface to control real robots:* The simulation environment is also capable of generating command sequences for real robot controllers. In this mode only those motion commands are output which have been verified with the built-in collision checking to be safe. Currently only the PUMA 560 robot with the Unimation controller running the VAL II robot control system [6] is supported, but additional output modules can be added.

## PLATFORMS

Implementations of ROBOSIM are currently available for the Hewlett-Packard HP 9000/300 and 9000/800 graphics workstation families, Silicon Graphics workstations, Intergraph workstations, and 386 or 486-based PC compatibles with EGA or VGA displays. The display mode may be wire-frame or shaded solid modeling for the workstation implementations. Currently, the PC versions display in wire-frame mode only. While currently limited to wire-frame displays, the PC versions are quite fast, offering displayed manipulator motions at speeds well in

excess of the hardware being simulated. It is the ability to run ROBOSIM at high speeds on a PC that makes the package an attractive tool for all engineering students studying robotics, kinematics, industrial automation, mechanisms, and advanced automation. Armed with their personal computer, students can design and operate quite complex robotic systems, gaining an excellent appreciation for the many factors that must be taken into consideration in industrial automation. The PC version will also open the door to simulation technology for many small businesses that can not afford expensive systems tailored to high-end workstation implementation.

### PLANS FOR DISTRIBUTION

The American Society for Engineering Education's 1992 *Directory of Engineering and Engineering Technology Undergraduate Programs* lists 261 engineering schools and 339 engineering technology schools in the U.S. [8]. The total undergraduate enrollment in the engineering programs was 358,095 with 61,318 B.S. degrees awarded in 1992. The total graduate enrollment in the engineering programs was 70,980 M.S. students with 26,006 degrees awarded in 1992, and 34,647 Ph.D. students with 5,582 Ph.D. degrees awarded in 1992. The total undergraduate enrollment in the engineering technology programs was 33,797 with 7,458 B.S. degrees awarded in 1992.

Based on an analysis of students who would be taking courses in robotics, mechanisms, kinematics, industrial automation, advanced automation, other courses involving design, control, and operation of mechanisms and structures in three-dimensional space, the number of potential users of ROBOSIM in the academic community is estimated to be in excess of 10,000 per year. NASA and Vanderbilt University are currently formulating a distribution plan to service this need. Plans are likewise being formulated to distribute an industrial version, which is anticipated to have strong appeal to small businesses engaged in special equipment design and other related areas where graphical simulation with fast motion display on a PC would be a valuable tool.

### FUTURE ENHANCEMENTS

The available experience with the ROBOSIM package suggests that it is a flexible and powerful tool for modeling and simulating robotic systems [9]. It has proven easy enough to understand and use in introductory courses on robotics, kinematics, industrial automation, and mechanisms, but its advanced features also make it possible to use in complex large-scale systems [10-13].

Some areas where future improvements are planned include:

- Programming language: A future version of ROBOSIM will be embedded into a general purpose interactive programming language interpreter. This new version will also support the old command syntax for backward compatibility, but the use of a general purpose language instead of the current command interpreter will offer several advantages:
  - Program flow control statements in simulations.
  - An easier way for users to specify inverse kinematic routines for their manipulator models.
  - An easier way for users to specify arm configuration selection and collision avoidance heuristics for their models.
- Development of a graphical user interface (GUI) to control simulation options: There are some system parameters in the simulation environment which are especially suited for control by GUI methods (while keeping the current interactive commands to control them as well). These include the camera setup, lighting model, and other similar options.
- Interface to common CAD packages for importing shape designs to be used in simulations.

- o Continued improvements on the path planning and arm configuration management heuristics.

## CONCLUSIONS

The ability of U.S. industry to compete globally will depend on an adequate supply of engineers and technologists trained in the application of robotics and automation to the problems of industry. The current slump in the U.S. robotics industry is due in part to this lack of a trained work force. Opportunities for students to take courses in advanced automation are currently centered primarily in major school having the resources to equip an expensive robotics laboratory. Additionally, safety issues and the need to continually upgrade and maintain these facilities has further limited the number of schools with world-class facilities. The wide use of ROBOSIM will allow all schools to provide students with the ability to study and develop advanced robotic systems in safety and at greatly reduced expense. Furthermore, as stated before, virtually all of the features that make ROBOSIM appealing to the academic community are equally useful to the industrial user, particularly small businesses. NASA and Vanderbilt University are jointly formulating plans to distribute ROBOSIM to both the academic and industrial communities.

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