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TEST AND VALIDATION FOR ROBOT ARM CONTROL DYNAMICS SIMULATION

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Abstract

The Flight Telerobotic Servicer (FTS) program will require an ability to develop, in a cost effective manner, many simulation models for design, analysis, performance evaluation, and crew training. Computational speed and the degree of modeling fidelity associated with each simulation must be commensurate with problem objectives. To demonstrate evolving state-of-the-art general-purpose multibody modeling capabilities, to validate these by laboratory testing, and to expose their modeling shortcomings, two focus problems at the opposite ends of the simulation spectrum have been defined:

(1) *Coarse Acquisition Control Dynamics*
Create a real-time man-in-the-control-loop simulator. Provide animated graphical display of robot arm dynamics and tactile feedback sufficient for cueing the operator. Interface simulator software with human-operated tactile feedback controller; i.e., the Kraft mini-master.

(2) *Fine, Precision Mode Control Dynamics*
Create a high-speed, high-fidelity simulation model for the design, analysis, and performance evaluation of autonomous 7 degree-of-freedom (dof) trajectory control algorithms. This model must contain detail dynamic models for all significant dynamics elements within the robot arm, such as joint drive mechanisms.

Successful completion of this project will require the cooperative efforts of several research groups, each focusing within a prime area of responsibility and jointly working within an interface area. Our intent is to utilize the recently developed recursive multibody dynamics algorithm associated with Order N Iowa, to create a real-time man-in-the-loop simulator for the Robotics Research Corporation (RRC) 7 dof robot arm in the Goddard Space Flight Center (GSFC) robotics laboratory. Man-in-the-control-loop will be via a fully interfaced Kraft mini-master tactile feedback controller.

We further intend to transport the recursive multibody dynamics equations to old DISCOS to create Order N DISCOS, a new high-speed, high-fidelity general-purpose control analysis capability. Pilot demonstration of Order N DISCOS will be via application to the precision control modeling needs associated with supporting RRC 7 dof robot arm autonomous controls design and analysis. Fine detail modeling will require detailed power train modeling in a format compatible with definition within Order N DISCOS. A series of control algorithms and associated sets of laboratory tests will be defined. These will be performed at GSFC and used to validate our ability to develop a broad range of high-speed, high-fidelity simulation capabilities in a cost effective manner.

1. Introduction

Recent advances in high-speed parallel processing computers, and new methods in dynamics formulation that exploit modern computer architectures have created a substantial increase in computational speed; consequently, dynamics simulation is, in some cases, even faster than real-time. Also, high-speed computer graphics generates high-fidelity animation of the simulation, and thereby creates realism sophisticated enough to give an adequate visual cue to the operator.

Here we demonstrate the use of such advanced technology; specifically, we develop, in a cost effective manner, simulation capabilities of the RRC 7 dof arm for design, analysis, performance evaluation, and crew training in support of the FTS program. The simulation model is to be validated with a series of experiments in GSFC to ensure that it represents the actual model to the highest degree of fidelity possible. Once validated, the simulation model is to be tied with high-speed computer graphics and the Kraft mini-master to give the operator visual and tactile feedbacks.

2. Development of Order N Iowa

Dynamics analysis of multibody mechanical systems requires formulation of the equations of motion in a differential equation form and associated constraints as nonlinear algebraic equations. In deriving the equations of motion, two basically different kinds of generalized coordinates are used; one is joint or relative coordinates between two contiguous bodies, the other is Cartesian or absolute coordinates of each body. The Cartesian coordinate formulation is quite general and treats open- and closed-loop mechanisms in the same way, but at the same time it introduces a maximum number of generalized coordinates and associated kinematic constraints. On the other hand, the joint coordinate formulation employs a minimum number of generalized coordinates and is directly applicable to open-loop mechanisms, but it requires some extension to treat closed-loop mechanisms.

In the recursive formulation [1,2], dynamics analysis can be divided into three major steps. First, by using the variational-vector calculus approach [3], the variational equations of motion are formed in Cartesian coordinates. At this stage, the known positions and velocities in either Cartesian or joint coordinates must all be expressed in Cartesian coordinates. For example, in the case of a robot arm, the base body is described with respect to the inertial frame, but the others may be described in relation to their neighboring members, namely, in joint coordinates such as joint angles and joint angular velocities. Then by starting from the base body and proceeding toward the tree-limb-end body the joint coordinate representation can be transformed to the Cartesian coordinate representation. Second, the variational equations of motion in Cartesian coordinates are transformed into the variational equations of motion in joint coordinates by recursive use of the kinematic relationship between two contiguous bodies. Third, the equations of motion are finally expressed in joint coordinates. From the equations of motion acceleration is found; then, through numerical integrations, velocity and position are found. This concludes one cycle of iteration.

The recursive formulation has been applied to a variety of mechanisms, and has successfully demonstrated its efficiency [1,2]. Furthermore, it is easily adaptable to the emerging parallel processing computers.

3. Development of Order N DISCOS

The DISCOS multibody dynamics software was originally developed for the Goddard Spaceflight Center during the mid-1970's for analyzing the response of a spacecraft that could be modeled as a collection of rigid and flexible bodies. Small displacement structural flexibility could be handled by allowing the spacecraft to be modeled by a general-purpose finite element code such as NASTRAN. By modeling individual bodies, rather than entire structures, the overall vehicle can experience both large motions relative to inertial space as well as large motions between individual bodies, without having to compute new structural parameters for each possible configuration. The basic DISCOS methodology makes use of advanced analytical dynamics formulation techniques that model individual bodies of the system and impose kinematic constraint conditions to force the correct overall system-level dynamical response.

The key to success in this approach is the use of the Lagrange multiplier technique in order to enforce the interconnection topology. This process successfully overcame several of the multibody formulation problems that had plagued earlier efforts at obtaining general-purpose software. The basic algorithm requires that the system-level Lagrange multiplier be computed during each integration step. The solution for the Lagrange multiplier is defined by a simple linear algebraic matrix equation whose dimension is governed by the number of constraint conditions which exist between contiguous bodies. Since the number of constraint conditions tends to increase more rapidly than the number of bodies, the calculation of the Lagrange multiplier linear matrix equation effectively limits the practical upper limit for the number of bodies which can be simulated. Although the exact number is somewhat problem-dependent, typical simulation runs with more than twelve bodies are not common.

As currently implemented, the DISCOS algorithm is now described as an order N^3 process, where N is the number of bodies in the multibody simulation. Clearly, as N increases, the computational burden is increasing at a significant rate, and real-time applications are not a practical reality. To support emerging needs for real-time autonomous robotics applications on the proposed space station, the current version of DISCOS is being upgraded to incorporate recently developed order N recursive multibody formulations. This upgrade, by Cambridge Research, will occur over a three-year period and is being carried out as part of the Industry/University Cooperative Research Center (I/UCRC) for Simulation and Design Optimization of Mechanical Systems at The University of Iowa. Order N algorithms allow the analyst to integrate the minimum dimension set of equations at the acceleration level. For a tree-like structure, the Lagrange multiplier calculations completely disappear from the calculations, though they can be produced if there is interest in loads information at joints. For ring-like structures, however, Lagrange multipliers are still required in order to deal with closed-loop systems. However, because the dimension of the Lagrange multiplier required is limited to the constraint conditions applied at a single hinge, the calculations are greatly simplified. Another significant advantage that the order N algorithms have over conventional order N^3 algorithms is that the basic computational structure is readily applicable to parallel implementations, as demonstrated in the pioneering work by the Iowa group. By combining both the recursive character and the ease of parallel implementation of order N algorithm, the proposed upgrade of DISCOS furnishes an enabling technology development for real-time on-orbit space station robotics activities.

Other planned enhancements for the DISCOS software include upgrades for event-driven activities such as (i) intermittent kinematic constraints (e.g., inequality constraint), (ii) intermittent loop closure (e.g., variable ring/tree topology for transitions between get and move and transitions between move and put operations for robots), (iii) multi-arm robot payload handoff (e.g., variable tree topology), (iv) constraint stabilization and momentum balance methods, and (v) differential/algebraic equation solution methods.

All planned upgrades of the DISCOS software are to be made so as to preserve the input/output characteristics of the existing software and to minimally impact the existing DISCOS user group. The evolving software capabilities will be validated with ground-based robotics tests at the Goddard Spaceflight Center during the summer of 1989 as well as being compared with the Order N Iowa software being developed at The University of Iowa

4. Dynamics Modeling and Simulation

As a generic model for space teleoperation, the RRC robot arm is simulated to support real-time man-in-the-loop control. The RRC robot arm has seven relatively rigid link segments connected at revolute joints [4]; each segment is a thin-wall exoskeletal structure. All the joints are directly driven by drive actuators directly mounted at the joints.

For dynamics modeling, the body reference frames are defined as in Figure 1, where all X-axes are defined along the joint rotational axes. The origin of each body reference frame is at the center of gravity of that body. Bodies 1 to 7 are identified as shoulder roll, shoulder pitch, elbow roll, elbow pitch, wrist roll, wrist pitch, and tool-plate roll, in that order. In addition, the home configuration is defined as follows: the roll axes of bodies 1, 3, 5 and 7 are on the same vertical plane; the roll axis of body 3 makes 60° with the roll axis of body 1; the roll axis of body 5 makes 30° with the roll axis of body 1; the roll axis of body 7 is perpendicular to the roll axis of body 1; all the initial joint angles are set to zero in that configuration.

The robot arm dynamics model has been created with the recursive formulation and simulated with parallel computation on an Alliant FX/8 multi-processor mini supercomputer

To estimate computation time for this model without any joint actuator, a free fall motion under gravity is simulated using different numbers of processors. Here the numerical integration is done by the Adams-Bashforth third-order method with a 10 milisecond constant step size. In Figure 2, the computation time with 4 processors is 4.35 miliseconds per time step, which means that it takes 0.435 second for 1 second real-clock time simulation. Furthermore, with 8 processors the computation time is only 2.77 miliseconds per time step; in other words, the simulation is 3.5 times faster than the real-clock time. The result of this simulation strongly indicates that the real-time man-in-the-loop simulation is feasible.

5. Control Algorithm Design

The MIT group is currently developing a model of the control system for the RRC robot arm. The configuration of the controller is the same for each of the seven joints, and consists of a velocity and torque compensator. The MIT model will include the effects of the electronics, amplifier, motor and harmonic drive in each joint, since these components are considered important in obtaining an accurate model. The current model takes into account the stiffness in the harmonic drives and viscous friction in the motors, harmonic drives, and links. The next

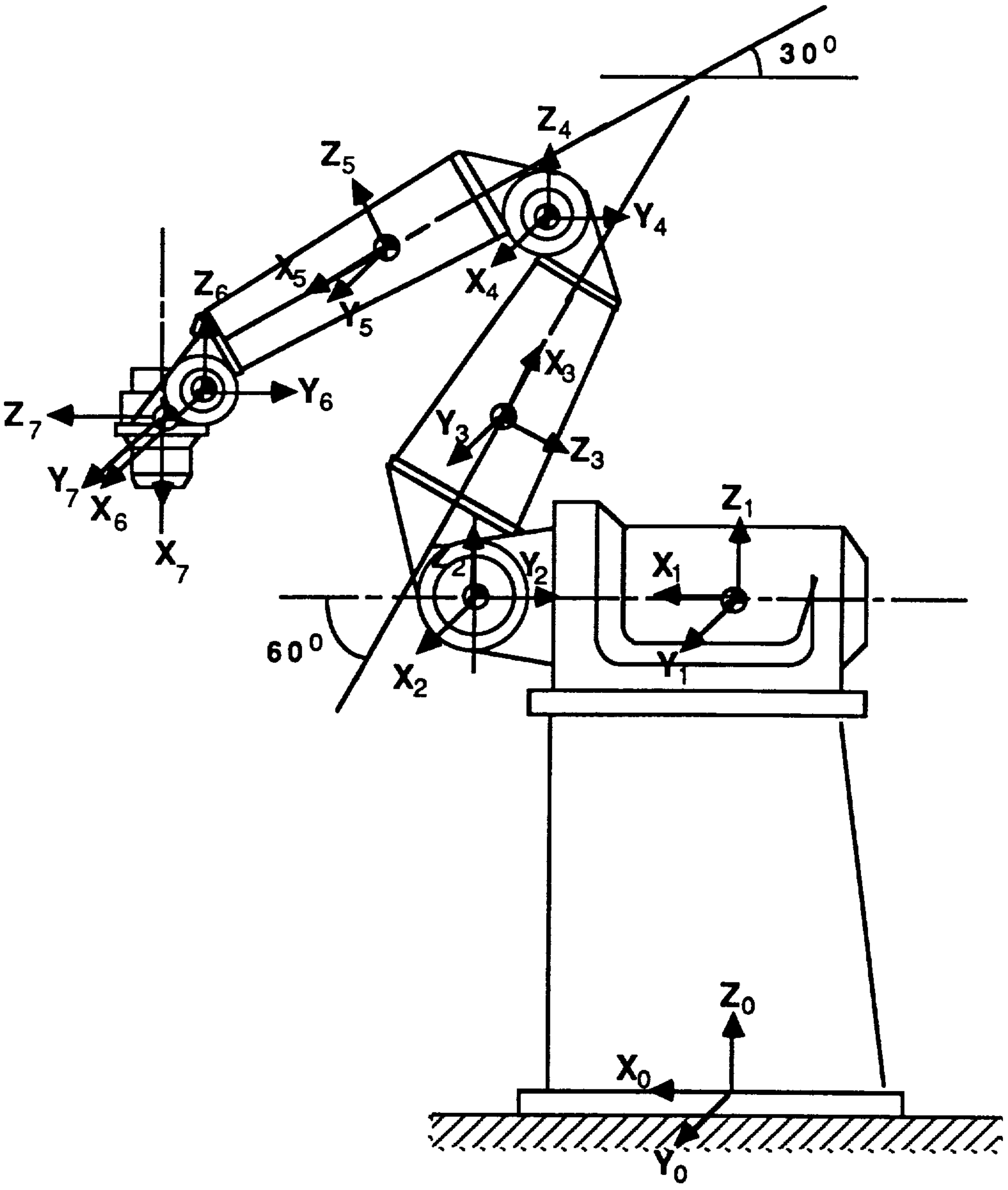


Figure 1. Body Frame Definition and Home Configuration

version of the model will include the effects of the motors and the nonlinear spring characteristics of the harmonic drive. Once this model is finished, it will be combined with the arm dynamics model being developed by Cambridge Research. The complete system model will be verified in both the time and frequency domains using results obtained by GSFC. If the model does not accurately predict the response of the real arm, the modeling assumptions will be re-evaluated and the model will be subsequently updated.

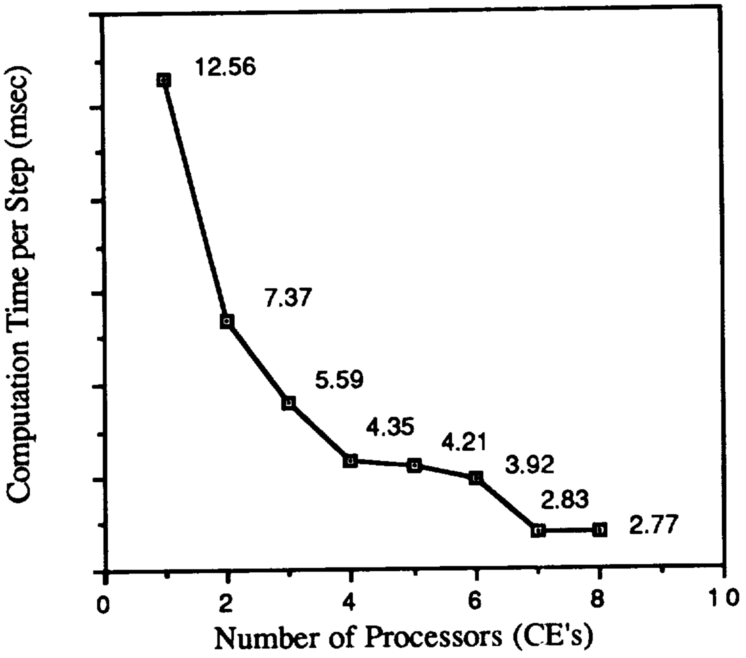


Figure 2. Computation Time on the Alliant

The experimentally verified model will be a very powerful tool for the analysis of new control algorithms. It will allow a researcher to make changes to the system and evaluate their effects without adjusting or replacing any hardware. This will be very useful when different control schemes are under consideration. Areas of future investigation include force control, adaptive control, and reduction of system vibration.

The choice of a particular control scheme is highly dependent on the nature of the task that the robot is to perform. For applications where the robot must interact with its environment, force control provides advantages over conventional trajectory control. The MIT group will examine the feasibility of such a scheme for the FTS. In situations where the model can not be determined accurately, adaptive control may provide an alternative. For example, the MIT group could develop a controller that generates force commands and then corrects for nonlinearities on the basis of the actual force measured at the end effector. For a system with flexibility in the robot or payload, vibration at the end effector could affect robot performance. If this is the case with the FTS, a technique recently developed at MIT can be applied for preshaping the command inputs to reduce vibration significantly.

6. Test and Validation

The controller at each joint of the RRC arm is built on the basis of an approximated linear model; therefore, its performance should be first tested within the vicinity of a certain configuration, where the load and arm inertia is nearly constant. In such a case, a small step or ramp input drives one joint while all the other joints are locked. The same experiment is to be performed throughout all the seven joints. Next, a large step or ramp input drives one joint at a time with all the others locked. This time, nonlinear dynamics will affect the performance of the joint controller, and will also influence the corresponding simulation.

Once we have confidence in the model and controller, more than one joint are to be activated and the robot arm thus maneuvers along a predetermined trajectory in space. During such a maneuver it is necessary that signals pertaining to applied torque and angular displacement and velocity be recorded at each joint for the verification of a dynamics model. Those two types of information, namely, torque and configuration, can uniquely determine the dynamics of the arm and reproduce the same dynamic behavior. In addition, for the verification of a control algorithm, it is also necessary that at each joint the command reference angle be recorded with the armature current in a servomotor. In other words, the analog signals from the resolver, the torque transducer, and the armature current at every joint should be digitized and recorded, so that each experiment produces two sets of data in the time domain: torque and configuration.

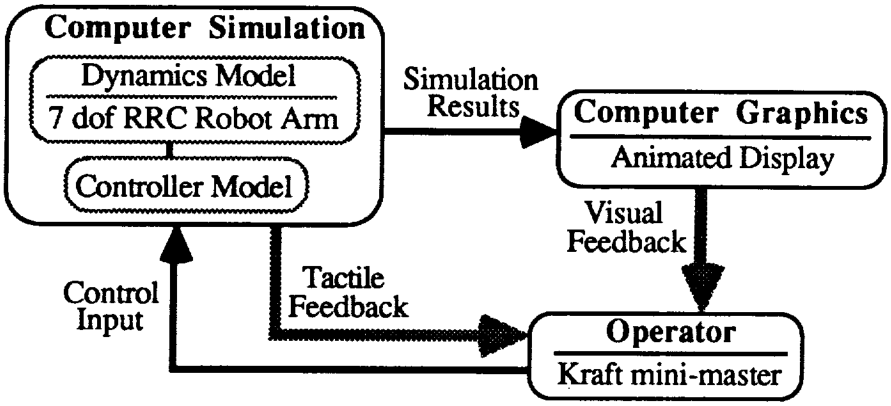
As a first step toward a correct dynamics model, the robot arm and the associated controller are to be simulated and compared using both Order N Iowa and Order N DISCOS. Such a comparison should help to eliminate errors in the simulation model.

Next, simulation results are to be compared with actual experimental data in terms of configuration and torque histories. An important task in such a comparison is first to match the initial configurations between simulation and experiment. Considering the fact that the dynamics of a robot arm can be completely described by configuration and applied torque, the experimental time histories of configuration and applied torque should be applied to the simulation model one at a time to examine how close the model is to the actual system.

First, when an experimental torque history is fed into the simulation model, the forward dynamics analysis produces the corresponding configuration history; that is, angular displacement, velocity, and acceleration in the time domain. Thus the two configuration histories, one from experiment and the other from simulation, can be compared. Next, an experimental configuration history is fed into the simulation model; then, the inverse dynamics analysis produces the corresponding torque history that would have caused the configuration history. This time these two torque histories can be compared.

7. Real-time Man-in-the-Loop Simulation

The operator, as shown in the diagram, is the decision maker in the control loop with visual and tactile feedbacks: visual feedback from computer graphics display of the RRC robot arm, tactile feedback from the Kraft mini-master that is interfaced through a serial port with the graphics workstation. His control action drives the dynamics and control simulation, which is carried out on a high-speed parallel processing system, such as an Alliant FX/8 mini supercomputer, to achieve real-time performance. The result from the simulation is sent to the graphics workstation via the Network Computing System (developed by Apollo Computer, Inc.) and is animated. At the same time, it is also sent to the Kraft mini-master to give tactile feedback to the operator.



For the animated display of dynamics systems, the I/UCRC at The University of Iowa has developed the Visualization of Dynamic Systems (VDS) program. It requires the simulation-updated position and orientation data specified by three translation values and Euler parameter vectors. The fidelity of the graphics animation is realistic enough to provide the operator with visual cueing comparable with TV cameras and video display screens. Furthermore, the animation can also be displayed in a split screen mode, or in two screens with moving view points to enhance depth and parallax perception.

8. Conclusion

Since flight simulators have proven cost effective for pilot training, their usage has been widely accepted throughout the airline industry. Now, a similar potential is on the horizon for mechanical systems. New recursive formulations for general purpose multibody dynamics simulation combined with high-speed parallel processing computers are now capable of creating real-time man-in-the-control-loop simulators in a cost-effective manner. Such a simulator of the RRC robot arm is to be built in support of the FTS program. Its usage is not only for crew teleoperation training, but also for man-machine interface studies aimed at enhancing the ergonomic design of the telerobot and controller. The methodology is easily adapted to new or modified system design concept or control algorithm. It can also be used as a valuable tool for the study of human cognitive and behavioral science issues, as they apply to the telerobotic system.

REFERENCES

[1] Bae, D.S., Hwang, R.S., and Haug, E.J., "A Recursive Formulation for Real-Time Dynamic Simulation," Advances in Design Automation, ASME, DE-Vol. 14, September 1988, pp. 499-508.

[2] Hwang, R.S., Bae, D.S., and Haug, E.J., "Parallel Processing for Real-Time Dynamic System Simulation," Advances in Design Automation, ASME, DE-Vol. 14, September 1988, pp. 509-518.

[3] Haug, E.J. and McCullough, M.K., "A Variational-Vector Calculus Approach to Machine Dynamics," J. of Mechanisms, Transmissions, and Automation in Design, Vol. 108, 1986, pp. 25-30.

[4] Karlen, J.P., Thompson, J.M., and Farrell, J.D., 1987, "Design and Control of Modular, Kinematically-Redundant Manipulators," Second AIAA/NASA/USAF Symposium on Automation, Robotics and Advanced Computing for the National Space Program.

[5] Dubetz, M. and Haug, E.J., "Real-Time Dynamics Simulation: A Design Optimization Tool," Technical Report R-5, Center for Simulation and Design Optimization of Mechanical Systems, The University of Iowa, 1988.

[6] Dubetz, M. and Kuhl, J. "A Network Implementation of Real-Time Dynamic Simulation with Interactive Animated Graphics," Advances in Design Automation, ASME, DE-Vol. 14, September 1988, pp. 519-524.

PANEL ON GRAPHIC OVERLAYS IN TELEOPERATION