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The Use of the Articulated Total Body Model as a Robot Dynamics Simulation Tool

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NOTICES

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FOR THE COMMANDER

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Director, Biodynamics and Bioengineering Division
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THE USE OF THE ARTICULATED TOTAL BODY MODEL AS A ROBOT DYNAMICS SIMULATION TOOL

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ABSTRACT

The Articulated Total Body (ATB) model is a computer simulation program which was originally developed for the study of aircrew member dynamics during ejection from high-speed aircraft. This model is totally three-dimensional and is based on the rigid body dynamics of coupled systems which use Euler's equations of motion with constraint relations of the type employed in the Lagrange method. In this paper the use of the ATB model as a robot dynamics simulation tool is discussed and various simulations are demonstrated. For this purpose the ATB model has been modified to allow for the application of torques at the joints as functions of state variables of the system. Specifically, the motion of a robotic arm with six revolute articulations with joint torques prescribed as functions of angular displacement and angular velocity are demonstrated. The simulation procedures developed in this work may serve as valuable tools for analyzing robotic mechanisms, dynamic effects, joint load transmissions, feed-back control algorithms employed in the actuator control and end-effector trajectories.

INTRODUCTION

Work in the aerospace environment presents special problems which can be handled remotely by the use of automation techniques and robots. During aerospace operations, robot arms and hands can be controlled by a distant operator through exoskeletal devices to perform tasks such as repairing failed equipment, rescueing astronauts and handling hazardous materials. These tasks require extreme manipulatability and dexterity. The development of the technology necessary to achieve the level of fine task performance required in aerospace operations involves an understanding of the three-dimensional kinematics and dynamics of robotic systems and of the control techniques for accurately manipulating these devices. At the Armstrong Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, the Articulated Total Body (ATB) model has been successfully used in the investigation of manikin and human body dynamics. In view of the model's dynamic simulation capability and the similarities between robotic arms and the human arm, an attempt has been made in this study to add an active driving feature to the ATB model's passive response capabilities in order to use it as a dynamics and feedback control simulation tool.

DESCRIPTION OF THE ATB MODEL

The ATB model was originally developed as the Crash Victim Simulator (CVS) model for the National Highway Traffic Safety Administration (NHTSA) by Calspan Corporation in the early 1970's to predictively simulate occupant motion during automobile crashes (Ref. 1). It was subsequently modified to address Air Force requirements and renamed the ATB model (Refs. 2-5). It has been used extensively to study human and manikin body dynamics in aircraft ejections, automobile crashes and rollovers, and other mechanical force environments (Refs. 6-8).

The ATB model is based on rigid body dynamics, allowing a system to be described as a set of rigid segments, coupled at joints which allow the application of torques as functions of joint orientations and rate of change of orientations. A typical initial body

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configuration for a human or manikin simulation is shown in Figure 1. External forces are applied to the segments through interaction with other segments, contact planes used to describe the seat, floor, control panel, etc., belt restraint systems, pressure fields such as those due to wind forces, and gravity. Each segment has a surface approximated by an ellipsoid which is used to define a contact surface, application points for external forces and a reference for calculation of the contact forces. Motion constraints can also be placed on or between the segments.

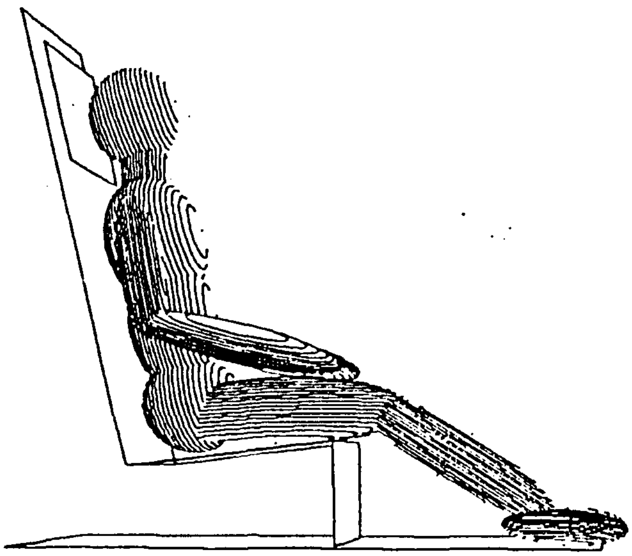

FIGURE 1. INITIAL BODY CONFIGURATION FOR HUMAN OR MANIKIN ATB SIMULATION

Many complex dynamic systems that can be described in terms of multiple rigid bodies can be modeled with the ATB model because of its generality and flexibility. An input data set consisting of the geometrical, inertial and material properties of the segments; the joint characteristics; definition of the environment, such as contact planes, belts, wind forces and gravity; and time histories of known motions defines a specific simulation for the model.

The ATB model provides a wide variety of options for output, including the time history data for the motion of all segments, transferred joint forces and torques, and external interactive forces. Also the associated VIEW graphics program provides three-dimensional projected images of the system as shown in Figure 1 for the human body (Ref. 9).

JOINT ACTUATORS

The above described features make the ATB model an ideal tool for modeling the dynamics of robotic systems. However, in the ATB model, which was originally designed to predict passive response, the system of rigid bodies reacted to external forces caused by the prescribed environment. To simulate robotic systems, an active driving capability had to be added to the model.

Robotic systems have actuators such as motors driving each joint articulation. These actuators typically apply a torque to the joint that drives the joint to a specific position or through a trajectory. The torques are adjusted by the feedback algorithms of the system. The active driving components of robotic systems are such actuators. Therefore the capability to model actuator response was added to the ATB model as the active element.

The most common state variables used in feedback control are the joint position and velocity. The model uses the positions and velocities of the system of segments to calculate all the forces and torques on each segment at each integration time step. These forces and torques include contact forces between segments and between segments and other surfaces or belts, aerodynamic forces, gravity and joint resistive torques. Since the actuators need this same information for the feedback algorithms, the actuator torque calculation was added to this part of the program. The program has been set up to feed back joint angle and velocity, enabling the use of position, derivative and integral control. At each time step in the program all the state variables are known and can be used as feedback variables for the actuators. Therefore variables such as linear positions or forces may also be used for feedback.

The actuator feedback calculation is contained in a subroutine that the user can modify to model the feedback algorithm required. Without modifying this subroutine, there is still considerable flexibility in the feedback provided by simply by changing the feedback parameters in the program input program input.

ROBOT SIMULATION

To test and demonstrate the use of the ATB model as a robotic simulator, an example robot with six articulations has been simulated. The input requirements for this simulation are representative of those for any robotic simulator including spatial geometry, inertial properties and joint position control information. The results of the simulations made of this robot demonstrate the ability of the ATB model to predict typical control system responses while taking into account the effects of inertial properties and gravity on system response.

Simulation Specification

To simulate any system the ATB model requires an input file describing that system and the surfaces that it may contact. The data describing the system consists of the mass, moments of inertia and geometry of each rigid link, the location and rotation axis orientation of each articulating joint and the characteristics of each actuator. The robot simulated is based on an American Cimflex MR6500 Merlin robot and the model's depiction of it is shown in Figure 2 with its six joints labelled. Mass and moment of inertia data were estimated from the limited mass data and geometric data available on the robot. For this simulation the planes and ellipsoids associated with the segments are used only for graphical display. If contact by a robot segment with another object was to be simulated the geometrical elements could be used to determine whether contact was occurring, the contact point on the segment and the contact forces. All of the segment and joint data are prescribed in each of the segments' local coordinate systems,

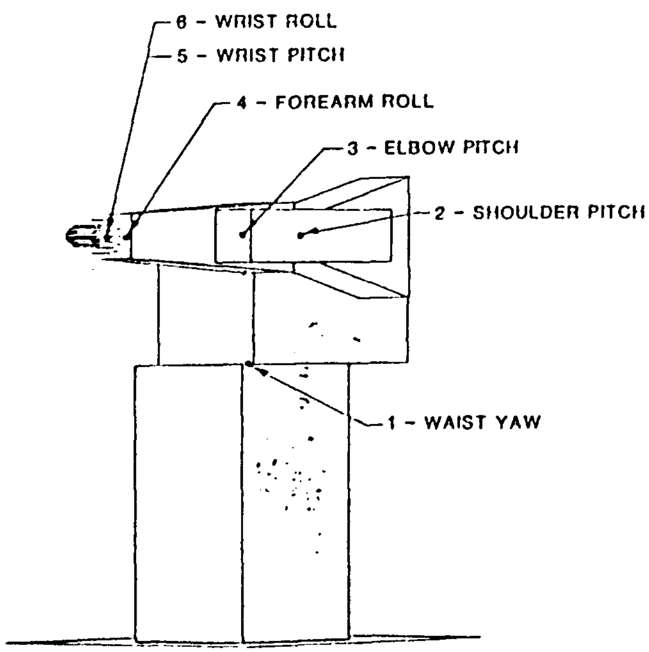

FIGURE 2. ROBOT ARM WITH SIX JOINTS

located at the segment center of mass. The joint locations and rotations axes orientations were measured and prescribed with respect to these local coordinate systems. The robot is shown in its home position and its articulations are defined as: waist yaw at joint 1, shoulder pitch at joint 2, elbow pitch at joint 3, forearm roll at joint 4, wrist pitch at joint 5 and wrist roll at joint 6.

Each joint was assigned an actuator, which applied torques as functions of the joint position variables, about the respective joint axes. The form of the torque feedback algorithm for each actuator used in the initial simulations is:

$$T = f_2(\theta-\theta_o) - f_3(\dot{\theta}) \qquad (1)$$

Where: $\theta_o = f_1(t)$,

T is the joint torque applied by the actuator,

θ is the joint angle,

θ_o is the joint target angle,

$\dot{\theta}$ is the joint angular velocity,

t is time, and

f_i are input functions.

The input functions can have a variety of forms including a constant, polynomial, tabular or combination. Simple functions were chosen for these simulations to test the program. The functions used were:

$$f_1(x) = a$$

$$f_2(x) = bx$$

$$f_3(x) = cx$$

The constants a, b and c used for each joint were varied to demonstrate different system responses.

Results

The robot motion for a simulation in which all the joints were driven to different angles is shown in Figure 3. The graphics program allows the simulated system to be displayed at any time step and from any viewing angle. The simulation also provides time history data on the segment positions and orientations, the joint orientations and torques, and the actuator torques. Figure 4 contains plots of all of the joint

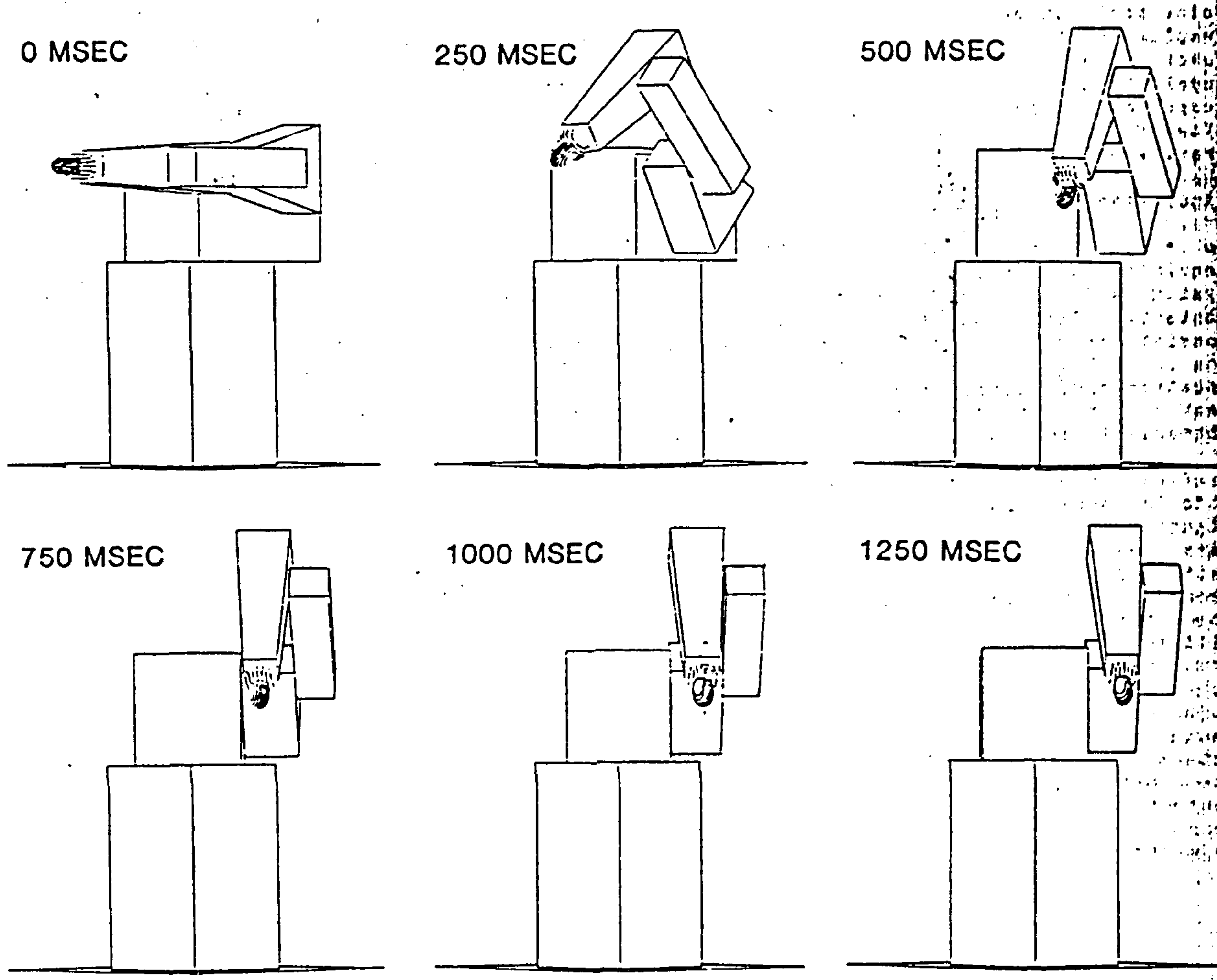

FIGURE 3. SIMULATED ROBOT MOTION

angles for the above simulation. These plots demonstrate several important characteristics of a dynamic simulation. The wrist pitch target angle was zero degrees, but the wrist does pitch slightly during the first 400 msec. due to the motion of the other joints. The shoulder pitch levels off at an angle slightly less than its 45 degrees target angle and the elbow pitch levels off at an angle slightly more than its 90 degrees target angle due to the torque required at each of these joints to compensate for the weight of the arm. It is also likely that the shape of the forearm roll plot is affected by the wrist roll.

Figure 5 contains plots from four simulations in which the wrist roll actuator was driven to 90 degrees and all the other actuators were driven to zero. The feedback parameters for the wrist roll actuator were varied to obtain the different wrist roll responses seen in the plots. The differences in the other joints' motions again demonstrate the inertial effects of the system. The forearm roll is especially affected by the large motions of the wrist.

DISCUSSION

In this study, we have demonstrated that the ATB model, with the active driving capability of the actuator modifications, can be used as a robotic dynamics simulation tool. It is intrinsic to the ATB program to account for the dynamic characteristics (or inertial effects) of the arm, as exhibited by the tim histories of the various joint motion in

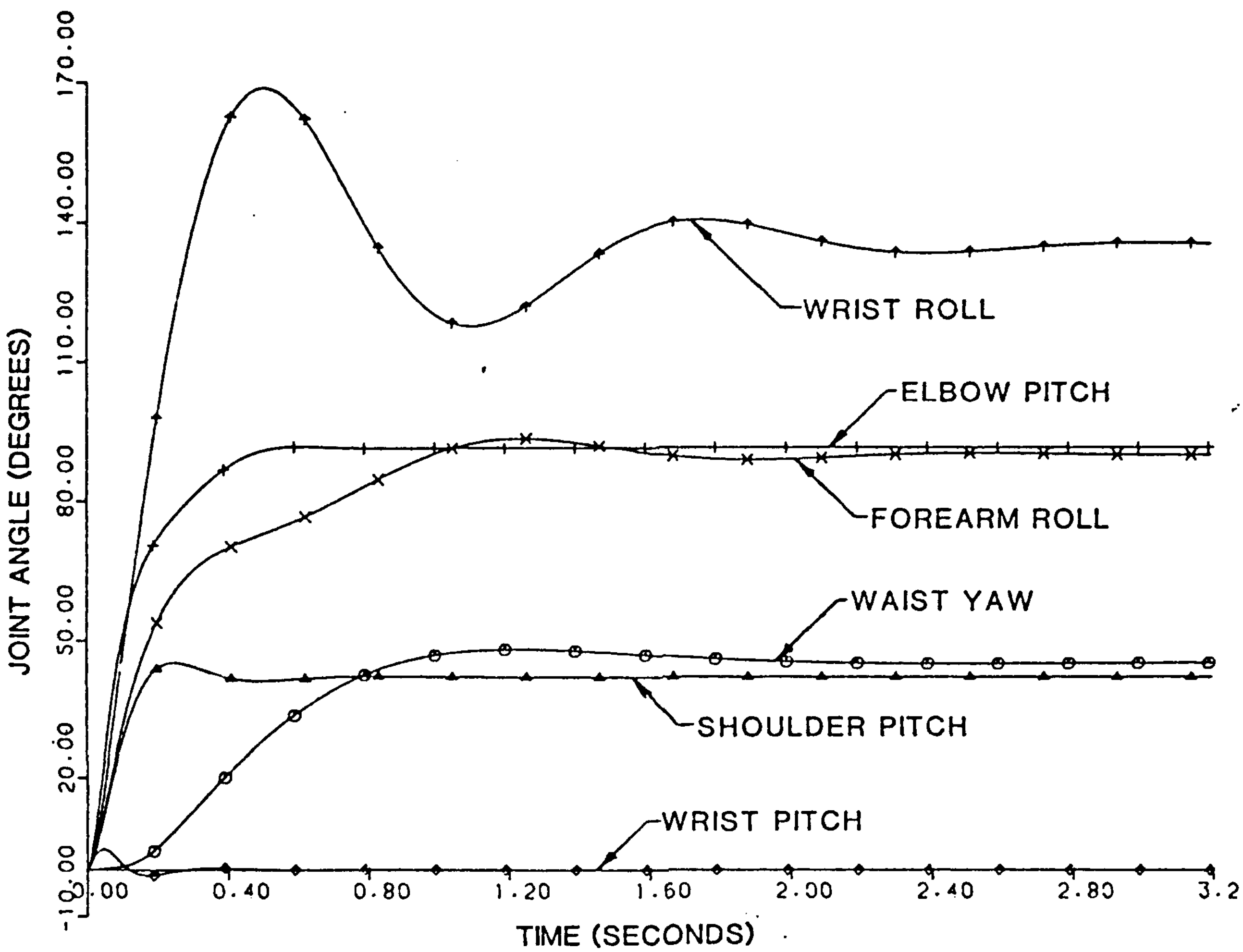

FIGURE 4. JOINT ANGLE RESPONSES

the robotic arm simulation (Figures 4 and 5). Although the segment yaw, pitch and roll angles are kinematic quantities, a pure kinematic simulation would not predict the responses demonstrated here due to its neglect of the inertia properties of the system. Bringing out the dynamic characteristics of the system under simulation has been proved to be one of several strengths of the ATB model. With its capability to incorporate a variety of environmental forces and torques and its flexibility to model different system structures, the model has been established to be a versatile tool for further development of robotic simulation methods.

Future work with the ATB model, could allow investigations of integral control, control algorithms which couple the motions of several joints, force control, and adaptive control. Because the model calculates all the state variables needed for each of these control methods at each time step, their dependence can easily be incorporated into the feedback subroutine developed in this study.

The next logical step in this work is a validation of the model predictions. This can be accomplished by exorcising a robot with the same structure, inertial properties and feedback algorithms and comparing its responses with those of the model.

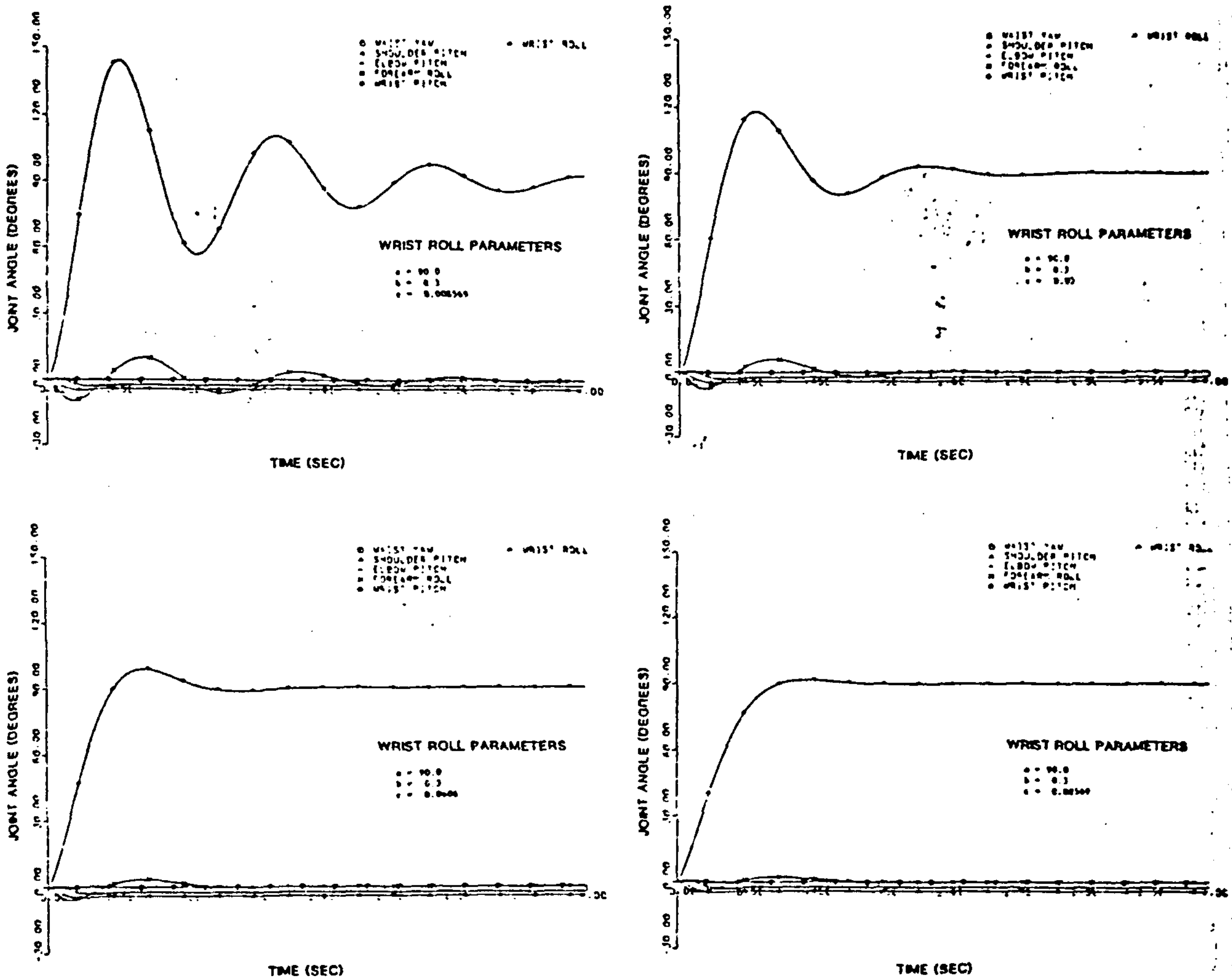

FIGURE 5. JOINT ANGLE RESPONSES

VARYING WRIST ROLL ACTUATOR FEEDBACK PARAMETERS

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