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A Statically Balanced Direct Drive Manipulator

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Abstract

A practical architecture, using a four-bar-linkage, is considered for the University of Minnesota direct drive robot [8]. This statically- balanced direct drive robot has been constructed for stability analysis of the robot in constrained manipulation [5 - 7]. As a result of the elimination of the gravity forces (without any counter weights), smaller actuators and consequently smaller amplifiers were chosen. The motors yield acceleration of 5g at the end point without overheating. High torque, low speed, brush-less AC synchronous motors are used to power the robot. Graphite-epoxy composite material is used for the construction of the robot links. A 4-node parallel processor has been used to control the robot. The dynamic tracking accuracy -with the feedforward torque method as a control law- has been derived experimentally.

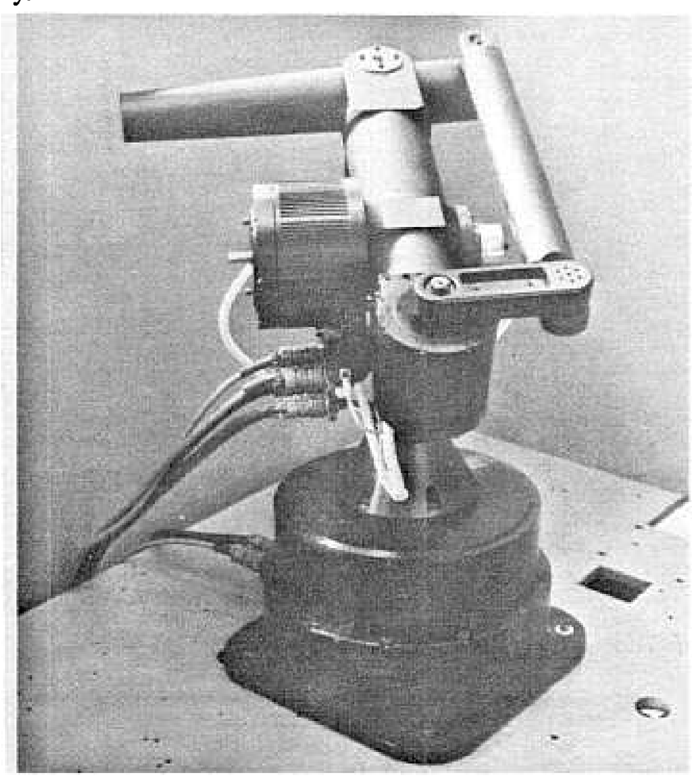

Figure 1: University of Minnesota Direct Drive Arm

Introduction

The work presented here is on the design and control of the Minnesota direct drive robot. This robot is statically balanced and uses a four bar link mechanism to compensate for some of the drawbacks of serial type [2] and parallelogram type [3] direct drive robots.

Conventional robot manipulators with electric servomotors are driven through speed reducers. Although speed reducers generate large torque, they usually introduce backlash, compliance, cogging, and friction into the systems. Studies on several industrial robots indicate that the powertrain compliance forms over 80% of total arm compliance [10]. Also the friction torque generated by reducer is about 25% of the total required torque in any maneuver [4]. Several attempts have been made to improve the manipulator dynamic behavior. Asada and Kanade [2] designed a serial type direct drive arm in which the actuators were directly coupled to links without any transmission mechanism. The elimination of the transmission mechanism improved the robot performance, however large motors were needed to drive the robot. Asada and Youcef-Toumi [3] studied a direct drive arm with a parallelogram mechanism to eliminate the problems associated with serial type robots. A direct drive arm with a counterweight was designed by Takase et al. [11] in order to eliminate the gravity effect at three major joints. Another direct drive arm, designed by Kuwahara et al. [9] to reduce the effect of gravity using a four bar link for the forearm, and a special spring for the upper arm. The counterweight provides the system balance for all possible positions, however it increases the total inertia of the robot arm. The spring balancing will not perfectly balance the system either.

In this research, a statically balanced direct drive arm is designed to achieve improved dynamic behavior. As a result of the elimination of the gravity forces (without any counter weights), smaller actuators and consequently smaller amplifiers were chosen. The motors yield acceleration of 5g at the end point without overheating.

Architecture

Figure 2 shows the schematic diagram of the University of Minnesota direct drive arm. The arm has three degrees of freedom, all of which are articulated drive joints. Motor 1 powers the system about a vertical axis. Motor 2 pitches the entire four-bar-linkage while motor 3 is used to power the four-bar-linkage. Link 2 is directly connected to the shaft of motor 2. The joint angles are represented by θ_1, θ_2, and θ_3. θ_1 represents the rotation of link 1. θ_2 represents the pitch angle of the four-bar-linkage as shown in figure 3. θ_3 represents the angle between link 2 and link 3. Shown are the conditions under which the gravity terms are eliminated from the dynamic equations.

Figure 3 shows the four-bar-linkage with assigned coordinate frames. By inspection the conditions under which the vector of gravity passes through origin, O, for all possible values of θ_1 and θ_3 are given by equations (1) and (2).

$$(m_3\overline{x}_3 - m_4L_5 - m_5\overline{x}_5) \sin \theta_3 = 0 \qquad (1)$$

$$g\ (mt_3 + m_5) - m_2\overline{x}_2 - m_3(L_2 - g) - m_4(\overline{x}_4 - g) - (m_3\overline{x}_3 - m_4L_5 - m_5\overline{x}_5) \cos\theta_3 = 0 \qquad (2)$$

where: m_i, L_i = mass and length of each link,

$\overline{x}_i$ = the distance of center of mass from the origin of each coordinate frame,

mt_3 = mass of motor 3.

Conditions (1) and (2) result in:

$$m_3\overline{x}_3 - m_4L_5 - m_5\overline{x}_5 = 0 \qquad (3)$$

$$g(mt_3+m_5)-m_2\overline{x}_2-m_3(L_2-g)-m_4(\overline{x}_4 - g) = 0 \qquad (4)$$

If equations (3) and (4) are satisfied, then the center of gravity of the four-bar-linkage passes through point O for all the possible configurations of the arm. Note that the gravity force still passes through O even if the plane of the four-bar-linkage is tilted by motor 2 for all values of θ_2.

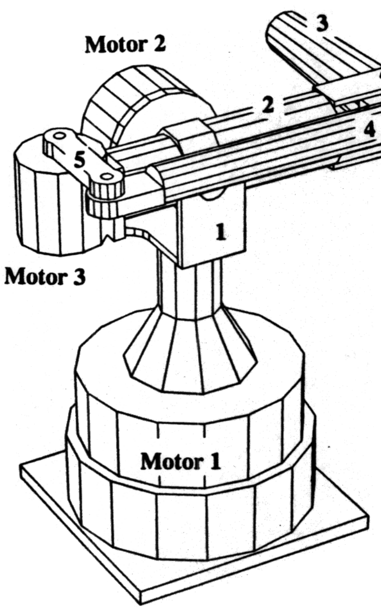

Figure 2: Schematic of University of Minnesota Arm.

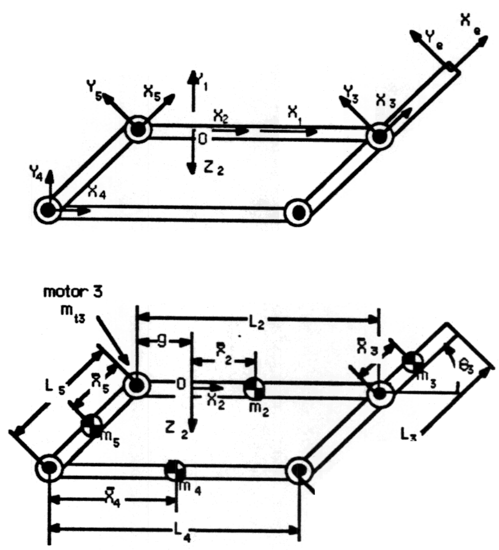

Figure 3: Four bar link mechanism

Hardware

A schematic of the system hardware is shown in figure 4. An IBM AT microcomputer which is hosting a 4-node parallel processor is used as the main controller of this robot. The parallel processor has four nodes and a PC/AT bus interface. Each node is an independent 32-bit processor with local memory and communication links to the other nodes in the system. A high speed AD/DA converter has been used for reading the velocity signals and sending analog command signals to the servo controller unit. A parallel IO board (D/D converter) between the servo controller unit and the computer allows for reading the R/D (Resolver to Digital) converter.

The servo controller unit produces three phase, Pulse Width Modulated (PWM), sinusoidal currents for the power amplifier. The servo controller unit contains an interpolator, R/D converter and a communication interface for the computer. The servo controller unit can be operated in either a closed loop velocity or current (torque) control mode (the current control is used). A PWM power amplifier, which provides up to 47 Amperes of drive current from a 325 volt power supply, is used to power the motors. The main DC bus power is derived by full-wave rectifying the three phase 230VAC incoming power. This yields a DC bus voltage of 325VDC. The motors used in this robot are neodymium (NdFeB) magnet AC brushless synchronous motor. Due to the high magnetic field strength (maximum energy products: 35 MGOe) of the rare earth NdFeB magnets, the motors have high torque to weight ratio. Pancake type resolvers are used as position and velocity sensors. The peak torque of motor 1 is 118 Nm, while the peak torques of motors 2 and 3 are 78 and 58 Nm respectively.

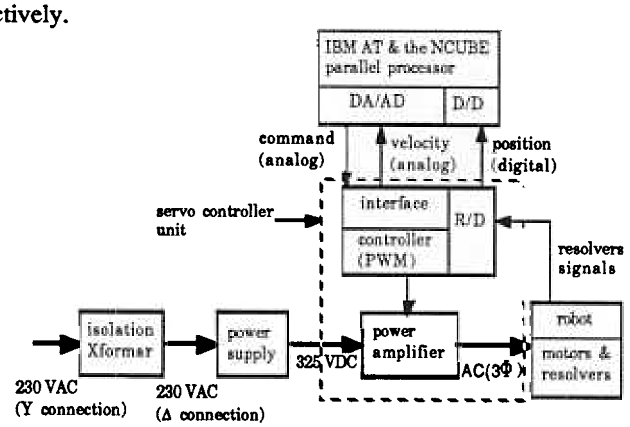

Figure 4: The control hardware for Minnesota Robot

Experimental Results

The preliminary evaluation of the performance of robot concerns the dynamic tracking accuracy along a specified trajectory. A feedforward compensator is used to cancel the robot nonlinear terms while a set of constant gains are used in the feedback loop to decrease the error and develop robustness in modelling errors [1]. The reference trajectory in the experiment is generated by a cubic polynomial. The motor dynamics and the friction in the dynamic model were included. The dynamic model does not include the gravity terms because the University of Minnesota Robot is statically balanced. The robot control program, written in C language, yields a 250 Hz sampling frequency. All the joints were commanded to simultaneously move 30 degrees in 0.3 seconds from a predetermined origin. The maximum velocity and acceleration for each joint are 150 degree/sec and 2000 degree/sec^2, respectively.

The trajectory and velocity errors for each joint are depicted in figures 5 and 6. Figure 5 shows the trajectory and velocity errors when all the robot parameters are calculated from the engineering drawings. The maximum tracking errors are 2.3°, 1.3°, and 2.3° for joint 1, 2 and 3, respectively. Figure 6 shows the trajectory and velocity errors with the dynamic parameters identified experimentally [8]. The trajectory and velocity errors are significantly reduced. The peak trajectory errors are 0.7°, 1.2° and 0.44° for joint 1, 2 and 3 respectively.

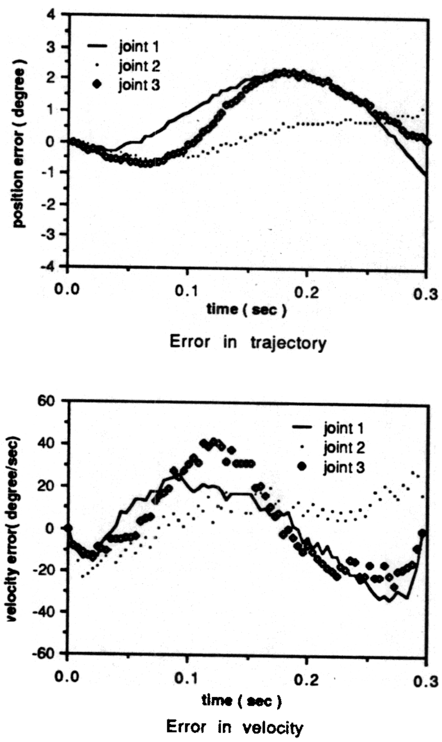

Figure 5: Trajectory and velocity error curves with the same trajectory for all three joints (All the parameters are computed from the engineering drawings)

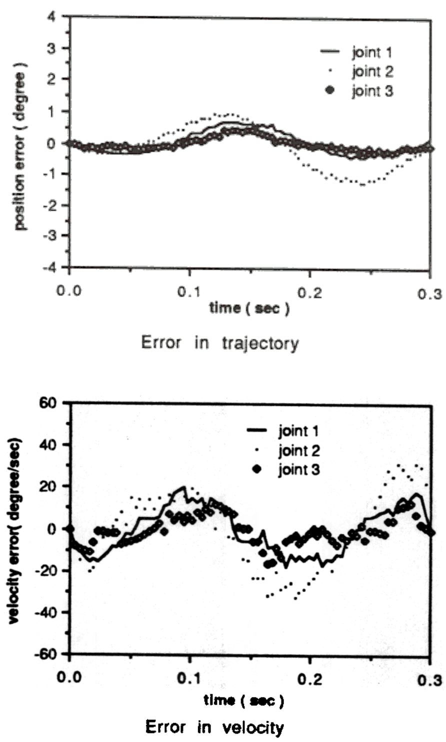

Figure 6: Trajectory and velocity error curves with the same trajectory for all three joints. (All the parameters are experimentally identified).

Summary

This paper presents some results of the on-going research project on statically-balanced direct drive arm at the University of Minnesota. The following features characterize this robot:

1. The statically-balanced mechanism without counter weights allows for selection of smaller actuators. Since in static or quasi-static operations, no load is on the actuators, therefore the overheating of the previous direct drive robots is alleviated.

2. The robot links are made of graphite-epoxy composite materials to give more structural stiffness and less mass. The high structural stiffness and low mass of the links allow for the wide bandwidth of the control system.

3. To improve tracking errors, the robot parameters were identified experimentally. The errors in the trajectory and velocity were reduced significantly.

4. Impedance control has been considered for control of the robot. The object of the control task is to develop a control system such that, this robot will be capable of maneuvering in constrained and unconstrained environments.

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