CMU Direct-Drive Arm: Previous Accomplishment

Direct-Drive Arm Concept

Present electrically powered manipulators are inferior to human arms and unsatisfactory for many applications in terms of speed, accuracy, and versatility. One of the reasons for this poor performance comes from the transmission mechanisms, such as gear trains, lead screws, chains and linkages, used to transmit power from the motors to the load and to increase the driving torque: they are the major cause of poor dynamic response, large friction, backlash, and loss of torque.

Recently, high torque, low speed motors using rare-earth magnetic materials have been developed and are becoming available for industrial use. Such motors have light weight and compact bodies. They allow us to eliminate transmission mechanisms from a robot arm so that each joint is directly driven (ie., direct-drive arm). In the direct-drive arm, all the joint axes are directly coupled to rotors of rare-earth magnet DC torque motors to obtain excellent features: no backlash, no friction, and low compliance. (See Figure 1) Because of its simple structure, a direct drive manipulator is composed of fewer mechanical parts than conventional manipulators.

The CMU Direct-Drive project started in the fall of 1980, and so far we have accomplished the following:

- We proposed a basic configuration of direct drive manipulators, developed a general procedure for designing them, and analyzed the feasibility of direct drive robot actuation in terms of weights and torques of joints [1].
- We designed and build the world-first direct-drive arm (CMU DD Arm I) with six degrees of freedom and a maximum external load of 6 kg.
- We have developed a control system using an LSI 11/23 and a VAX 11/750, and have performed the characteristic analysis and basic feedback control experiments. [2,3,4]
- We have developed the model of arm dynamics by the recursive Newton-Euler formulation. Based on this formulation a simulator of arm dynamic motions was written together with graphics

capability on PERQ. [5,6,7]

- Using the model of dynamics, we have applied feedforward compensation to the control of multi-degree-of-freedom motion in order to compensate for interactions among multiple links, and Coriolis, centrifugal and gravitational forces. [4,8]
- We have developed a digital servo processor (DISP) for multi-input multi-output control, which is interfaced to the Q-bus of the LSI-11/23 processor.

Based on our experience with this CMU DD Arm I, we propose the development of the second version, CMU DD Arm II, for which we seek for an industrial partner. This document includes the summary of the results we obtained from the CMU-DD Arm I, the general plan for the DD Arm II, and the progress to date.

Summary of CMU DD Arm I

Hardware

Configuration

6 revolute axes
R-P-R-P-R-P   P=Pivotal joint, R=Rotational joint
(See Figure 2)

Drive system

Direct-Drive by electric DC torque motors

1.	Magnedyne	Inc.	232-06 x 1
2.	"	"	444-01 x 2
3.	"	"	223-04 x 1
4.	Inland	Motor	QT7802 x 2
5.	"	"	QT2603 x 1
6.	"	"	QT2603 x 1
(option 7.	"	"	QT2404 x 1)

Controller

Control computer LSI 11/23
Host computer VAX 11/750

Servo amplifier

1.	CSR	Contraves	NC414	DC Servo Controller	x 1
2.	"	"	"	"	x 2
3.	"	"	"	"	x 1
4.	"	"	"	"	x 2
5.	"	"	NC407	DC Servo Controller	x 1
6.	"	"	"	"	x 1

Shaft encoder

#1, 3, 5, 6, (7)	Itek RI13/15MQ (13 bits Incremental)
#2, 4	Itek MS15/16 (15 bits Absolute)

(We do not use any tachometers, but measure the speed by differentiating the output of position encoders.)

Physical Dimensions

Arm Length:	Total	1700mm
	Base - Joint 2	765mm
	Joint 2 - Joint 4	510mm
	Joint 4 - Joint 6	315mm
	Joint 6 - Tip	110mm
Arm Weight	Total	250kg
	Motors (total)	91kg

Performances

Load capacity:	5 Kg (at the tip)
max. velocity:	3.5 m/sec (at the tip)
Positioning accuracy:	~ 0.05 mm (repeatability)
	~ 5 mm (absolute)

Joint #	Working range (deg)	Maximum velocity (deg/sec)	Peak torque (Nm)	Delay time (msec)	Settling time (msec)	Repeatability (deg)
1	+- 150	180	204	365	752	+- .045
2	+- 90	180	136			
3	+- 90	180	81.6			
4	+- 90	180	54.4	82	193	+- .035
5	+- 150	360	6.8			
6	+- 90	360	6.8	57	146	+- .003

(See the attached technical reports [4] for more details)

Computer System and Software

System Configuration: Figure 3

- Host:
  - o DEC VAX-11/750 running Berkeley 4.1 UNIX.
  - o 2 Mb Physical Memory
  - o 456 Mb Disk Storage
- Slave:
  - o DEC LSI-11/23 with a floating point option
  - o 128K Physical Memory
  - o Special Digital Servo Processor (DiSP) (under testing)

A VAX-11/750 serves as the primary computer for software development. The VAX is connected to an LSI-11/23 via a serial I/O line and by a high speed direct memory access (DMA) link [9]. The LSI-11 acts both as a monitor of the arm position and velocity, and as a controller in the joint servo-loops. The LSI-11 monitors the state of the arm by constantly measuring and recording joint positions and velocities for subsequent performance analysis. Control is realized in two forms. In analog control, hardware servo-loops for each joint are supplied reference angles by the LSI-11 in a classical control scheme. The alternative to this, digital servo control, is accomplished by placing the LSI-11 and DiSP directly into the feedback path. The DiSP can perform high speed (~200 nsec) multiplications to allow for multi-input, multi-output control of the form,

$$u = [K_p](q_r - q) + [K_v](\dot{q}_r - \dot{q}) + [K_f](f_r - f)$$

where q is the six-dimensional joint angle vector, f is a force-moment vector, and $[K_p]$, $[K_v]$, and $[K_f]$ are 6x6 gain matrices. The computation time of this equation by the DiSP is less than 1 msec.

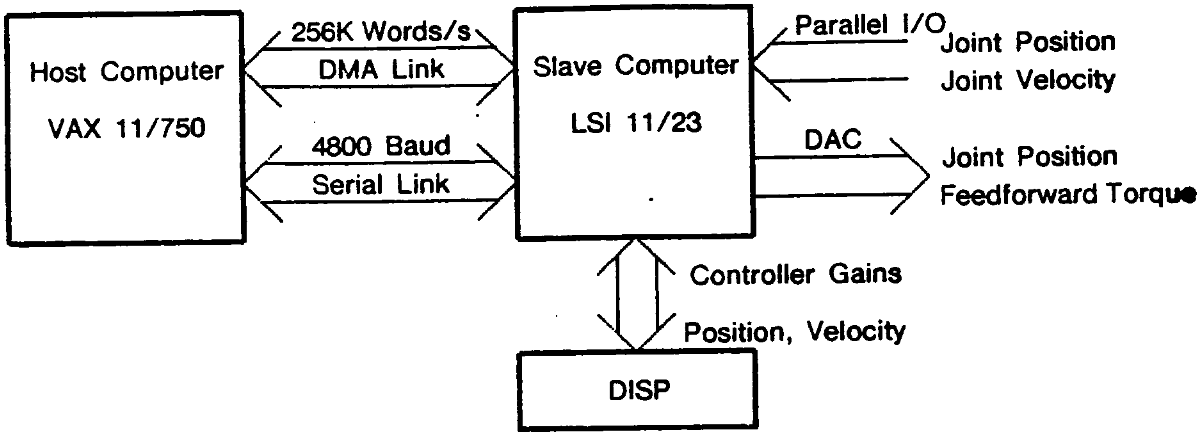

Figure 3. Computer system configuration

DD Arm Software Testbed

In any experimental setup, a software testbed is invaluable in analyzing system performance. To aid in the analysis of the Direct drive arm, a flexible software package was developed [3]. Features of the package include:

- a powerful command interpreter that prompts for missing arguments, performs bounds checking on all user supplied values (a critical requirement in safe manipulator movement), and offers an on-line help facility.

- All commands may be entered by user interactively, or read from a command file. These modes may also be freely intermixed.
- Extensive graphics capability. Recorded joint motions *etc.* can be viewed on a Tektronix graphics terminal or sent to a Xerox laser printer.

Specific functions of this package are:

- a Teach-and-Playback mode. This mode allows one to manually move the arm through a sequence of positions which are recorded by the software. The arm can then be instructed to repeat this motion a desired number of times. This sequence can be saved on a file for subsequent re-use. If any change is desired in the sequence, the dataset can be edited.
- an experiment mode. A wide variety of options are available in this mode. The primary use includes:
  - o Frequency response tests
  - o feedforward experiments
  - o digital control by use of DiSP

Coupled with this is a flexible graphics package which permits plotting of many manipulator variables such as joint position, joint velocity, tip motion in world coordinates and Bode diagrams.

Inverse Arm Dynamics and Simulator

The ability to simulate the motion of a robot manipulator allows greater flexibility in the design and development of the manipulator and its controller. A general purpose simulator has been developed and used to simulate and control the CMU direct drive arm.

Inverse Arm Dynamics

The inverse arm dynamics problem is that of computing torques and motor voltages which will move an arm along a desired trajectory. For doing this we have developed the efficient Newton-Euler formulation of the arm dynamics model. The torque of joint *i* is given by

$$\tau_{ri}(\theta_r) = \sum_{j=1}^{n} J_{ij}(\theta_r)\ddot{\theta}_{rj} + \sum_{j,k=1}^{n} b_{ijk}(\theta_r)\dot{\theta}_{rj}\dot{\theta}_{rk} + f_{gi}(\theta_r) + f_{ci}(\dot{\theta}_{ri}) \tag{1}$$

where J_{ij}, b_{ijk} and f_{gi} are functions of θ_{r1}, θ_{r2}, ..., θ_{r6} and f_{ci} is Coulomb friction and viscous friction at brushes and bearings. Using this equation, we can compute torques for any desired position, velocity, and acceleration in less than 10 milliseconds on VAX 11/750. This will allow us to use these calculations in real time. This program can work for any robot arm whose kinematic configuration is represented by the Denavit-

Hartenburg convention (See the Table 1.), and whose parameters for dynamics (eg, mass, inertia, etc) are given.

Table 1

Denavit-Hartenburg convention notation for the Direct Drive Arms

	DD Arm I				DD Arm II (tentative)		
Joint	R	A	α	Joint	R	A	α
1	0.765	0.000	90.0	1	0.000	0.000	0.0
2	0.000	0.000	-90.0	2	0.000	0.500	0.0
3	0.510	0.035	90.0	3	0.000	0.500	90.0
4	0.000	0.000	-90.0	4	0.000	0.000	90.0
5	0.315	0.000	90.0	5	0.200	0.000	-90.0
6	0.000	0.000	-90.0	6	0.000	0.000	90.0

Simulation

By encoding data about the manipulator from the mechanical drawings we can compute the critical parameters which describe the arm's dynamic characteristics. These parameters can be used with a recursive Newton-Euler technique to obtain the accelerations of the manipulator joints given the state of the arm and the torques applied to the joints. By integrating the accelerations, new positions and velocities can be determined. This, in effect, simulates the motion of the manipulator. We can simulate arm movements in approximately 50 times real time.

The simulation can then be displayed on a graphics system and compared with the trajectory of the real arm. This allows us to view motions that would be dangerous or impossible for the real arm to perform. It also allows us to test out experimental controllers without risking loss of control of the arm and it allows more than one person to perform tests on the manipulator. (See Figure 4 for an example of simulation results.) The characteristics of the direct drive arm, such as low friction, no backlash, and low loss of torque, allow the model to be much more exact than is possible with conventional arms.

Development of the Arm Control System

Basic Characteristics and Feedback Control

We have performed the analysis of basic characteristics and the feedback control of the direct-drive arm. (See the attached report [4].) Our experiments include:

Frequency response characteristics

A single-joint control system was built for each joint and the frequency response characteristics were measured. The parameters of actuators have been identified to design the basic feedback control.

Measurement of speed by optical shaft encoders

Electronic circuits have been developed to measure the angular velocity from the reading of precision optical shaft encoders. We have shown that the velocity can be measured from low speed (1°/sec) to high speed (360°/sec) (See attached report[2]). The velocity measurement is important to provide appropriate damping in controlling the DD Arm.

Step responses

At critical damping, the step responses of each joint were measured. The delay time for a large step input is from 50 msec (for joint 6) to 350 msec (for joint 1).

Steady state characteristics (repeatability and stiffness)

After the addition of phase lag compensation, the positional repeatability was found to be from 0.005° (for joint 6) to 0.019° (for joint 1). The stiffness obtained under the phase lag compensation was found sufficiently large and comparable to the Stanford Manipulator.

Feedforward Control

The inverse simulation program can be used to implement a feedforward control scheme which uses computed torques given a desired trajectory. Ideally, if the identification of the arm is perfect and no disturbing torque is applied to it, the arm can move along the specified trajectory with the computed torques. Of course, due to model inaccuracies we still require a feedback control system. By combining the feedforward control with the feedback control, we can expect that the former provides the gross torques to lead the arm to a given trajectory with no delay and that the latter provides the fine error correction to keep the state of the arm close to the reference. It has been demonstrated that by this method we can actually compensate various non-linear forces (eg, interaction between links, Coriolis force, and gravitational force). (See Figure 5 (a)(b).) This feedforward compensation is especially important in high speed motions: we have achieved the tip speed of 3.5 m/sec in following a circular trajectory.