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of few feet. All the commands can be sent from the terminal and the sensor readings are directly displayed on the terminal. In case of an unexpected situation, the operator can turn the robot "off" by pressing an emergency stop "red button." In few cases, where human intervention is necessary, the design balances the robot's strength, size and movements against a typical user.

The robot is controlled in a safe manner: the commands to the robot are routinely checked for their potentials to create a dangerous situation. For instance, the speed of the primary axes of the robot is kept limited by both electronic and software means. The static and dynamic forces created by the load at the end-effector are kept within the load capacity and dynamic response of the robot.

Additional care is taken to ensure that shut down, accidental removal or variation of level in the power source does not result in a hazardous condition. For instance, the power failure does not cause release of the load from the gripper as the robot is equipped with a mechanical gripper.

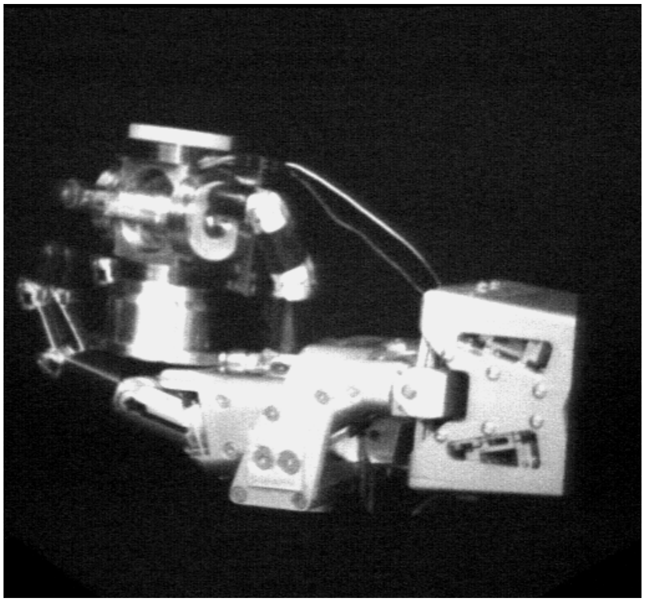

Figure 3: **A direct drive pointing device.**

6 The Future

In parallel, we have also explored alternate technologies that are suitable for teaching robotics. One approach has been to develop miniature direct drive robots that are ideal for teaching as they are inexpensive, simple and safe.

The key components are very low cost direct drive DC motor actuators. The motors are based on Nd-Fe-B rare earth permanent magnets and controlled by low cost microcontrollers. The motors have low friction, small size, high speed, low construction cost, no gear backlash, operate safely without limit switches, have limited self-braking, and generate moderate torque. Significantly, one motor can generate enough torque to lift a second motor of about the same size against the force of gravity, at a distance approximately equal to the size of the motor, without resorting to the use of a counterweight.

The very low cost (about $10) of miniature DD motors makes them attractive for our educational usage. Students in our robotics lab, including secondary school interns, build mini DD motors as a lab assignment. In particular, some students have built a small two link direct drive manipulator. They then related its kinematics, statics and dynamics to the simple two link planar manipulator theory (see e.g. [1,4]) they learn in class.

Acknowledgement

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points. Next, they calculate the joint velocities at the via points. For each segment (for n via points, there are $n-1$ segments), the velocities are different. Using the inverse kinematics procedure, they compute the joint angles at each via point. The points in the joint space are joined by the cubic polynomial trajectories of the previous experiment.

- **Experiment 4. Control of a D.C. Motor**.

The purpose of this experiment is to familiarize the students with the basic operation of D.C. motors. For this experiment, the students use simple position control of one joint.

To understand the control of a D.C. motor, the students first derive the equations describing the motor. The final equation is of the following form:

$$V = a\frac{d^2\theta}{dt^2} + b\frac{d\theta}{dt},$$

where $a = (JR)/K_T$ and $b = K_E$ = the back EMF constant. Here, J = the rotor inertia, R = *terminal resistance* and K_T is called the torque constant. V is the applied voltage for the D.C. motor.

In other words, the control input, V affects the joint motion, $\theta(t)$, through a second-order linear differential equation. The coefficients (a, b) of the differential equation depend on the motor construction only.

The students use the following two kinds of controls:

Model-Based Control:

For trajectory tracking, following model-based control law is used:

$$V = a(\ddot{\theta}^d - K_v\dot{e} - K_p e) + b\dot{\theta},$$

where $e = \theta - \theta^d$, and $\dot{e} = \dot{\theta} - \dot{\theta}^d$.

PD Control

PD control is used when there is no model of the system. For example the following control law is used for trajectory tracking:

$$V = -K_v\dot{e} - K_p e.$$

- **Experiment 5. Robot Arm Dynamics and Control**.

The students are asked to derive the dynamics of the ED I robot using a given mass distribution of the links and evaluate and compare the inertia force terms with the centrifugal and Coriolis force terms for three ranges of joint velocity (0 to 1/3 of maximum joint velocity, 1/3 to 2/3 of maximum joint velocity and 2/3 to 1 of maximum joint velocity).

Next, they design, implement and compare position control algorithms, using following two approaches: *joint-space control* and *task space control*.

In addition there were several term projects. The laboratory class was considered successful as all the students in the class did finish at least four out of the five experiments listed above.

5 The Safety Issues

ED I robot was designed to meet the most stringent of the safety standards as the potential for hazardous situations is extremely high with novice users. For instance, the design, construction, programming, operation and maintenance of ED I meets the ISO 10218 safety standard (Document: Manipulating Industrial Robots—Safety).

Several technical measures are employed in order to prevent accidents, and are based upon the following principles:

- The absence of humans in the safeguarded space during automatic operation.
- The elimination of hazards during intervention (e.g. repair or maintenance) in the safeguarded space.

The design and installation of the robot was carried out in a manner such that for routine operations of the robot (as in carrying out an experiment) no direct human intervention is necessary. The robot in its encased surrounding (a lexan enclosure equipped with a “guard mechanism”) is operated from a terminal at a distance

The *low level axes driver interpreter* then translates the commands dispatched by the `VxWorks`^{tm} into still lower-level commands that are executed by the Creonics motion controller card.

Executing a high-level robotic task on ED I involves simply writing C code sprinkled with library calls. Thus, the user accomplishes all of the numerical computation, user interface, error handling, data structure organization and temporal ordering of the actuation and sensing using the primitives provided by the C language, a set of standardized data structures, and some related libraries (e.g. `math.h`). The compiled and linked code then automatically runs the robot in the intended manner.

The `VxWorks`^{tm} real time system loads and runs (see [7]) a set of concurrent routines, generated by the compiler, which are synchronized by means of (i) *semaphores* and (ii) *message passing*. The real-time nature of the system is obtained by means of a prioritization scheme (i.e. privileges) and by supporting a wide variety of styles of command executions.

4 Laboratory Experiments

The laboratory section for the "*Introduction to Robotics*" course was designed to assist the students in learning the fundamental robotics concepts. The course develops analytic models of robot mechanisms, actuators and the robot's operating environment. It emphasizes foundational concepts, involving the geometry and algebra of rigid motions, forward and inverse kinematics of mechanical linkage systems, dynamics of actuators and linkages, task and trajectory planning as well as the algorithms for robot command and control. Prerequisites are introductory calculus, basic linear algebra and moderate experience with C programming language.

The laboratory section of the course involved four experiments, each experiment taking roughly two to three weeks:

- **Experiment 1: System Familiarization and Robot Kinematics.**
  Introduction to the system, consisting of the robot, its actuators, its control units, the interface, and the computer system. The students are shown some demonstrations illustrating how to read feedback signals and to command joint movement of the robot. The students then perform some simple experiments and familiarize themselves with basic robot operation.

  The lab instructor starts by discussing the safety issues and then demonstrating how to power up the system, how to use the editor, how to compile the programs, etc. Students run two sample programs: TESTMOVE and SENSR (joint-move and position-sensor programs).

  Next, the students measure the link lengths of each of the two links on the ED I robot and using these, compute, program and run various experiments dealing with the forward and inverse kinematics.

- **Experiment 2. Positional Control of the Joints.**
  In this experiment, the students are asked to write a procedure to take as input values for M, ω, and T and plan a trajectory for the JOINT1 (θ_1) determined by the equation

  $$\theta(t) = M \sin \omega t,$$

  where t is the time which increases by units of size STEP and $\theta(t)$ is the value for the angle of JOINT1 at time t.

  Next, the students are asked to generate a cubic polynomial trajectory motion for JOINT1 moving from an initial angle to a final angle–the cubic polynomial is based on the initial angle, an initial velocity, the angle, a final velocity, and the amount of time to move from the initial configuration to the final.

  These procedures are followed by experiments involving the movement of two and more joints.

- **Experiment 3. Trajectory Generation.**
  In this experiment, the students are asked to write a path planning program which uses the cubic spline method for joint space trajectory generation.

  Given an initial configuration and a final configuration, the students start by computing n via

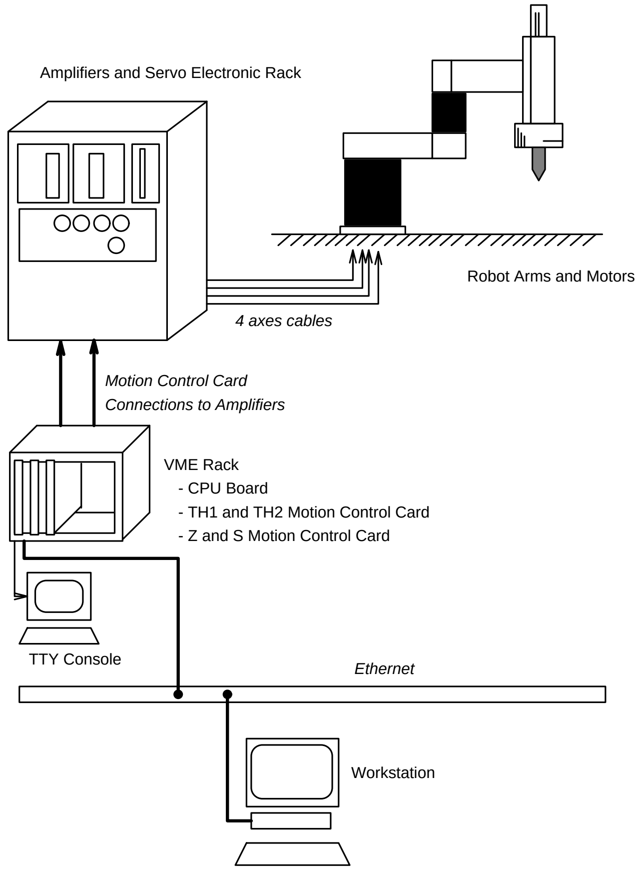

Figure 2: **Lay out of ED I.**

The structure of the z and the spindle (ρ) axes of ED I is somewhat unique. The z axis is a linear actuator that moves the end-effector vertically by a ball-screw mechanism connected to a Yasukawa motor housed at the top of the z axis. There are four members that guide the linear axis. Two of them are *precision ground shafts* with linear bearings that provide significant amount of rigidity to the spindle axis, while letting the entire mechanism to travel up or down with ease and precision. Third member is a *precision ball-screw drive* that transforms the rotary motion of the Yasukawa motor to the linear motion of the z axis. The fourth linear guiding member is the spindle itself and is composed of a *precision linear ball-spline*, holds the end-effector device, and is actuated by the spindle motor (Inland Motor) using direct-drive technology.

The linear ball-spline member of the linear axis is threaded to accept various end-effectors: 3-jaw chucks, parallel-jaw grippers and pinch-type grippers, Zebra force-sensing wrists, Hall-effect sensor, and digital cameras.

3.2 Electronic Hardware

The robot is operated by a digital controller which consists of a CPU (Motorola MVME147S), and two motion control cards (Creonics 2-axis MCC), one for each pair of motors (i.e., one for θ_1 and θ_2 axis-pair and another for z and *spindle* axis-pair). The CPU and the MCC's communicate via a high bandwidth (40 Mbit/sec) VME bus. The digital controller receives commands from the computer running the interface and generates appropriate commands for the actuators. In addition to the actuators that the motion control cards control, we also have *servo amplifiers for the actuators*, *digital encoders* and *encoder and drive power supplies* in order to run a closed-loop servo control scheme on the motion control cards.

The Creonics MCC is ideal for our purpose as it provides for each axis a closed-loop control for point-to-point positioning with *velocity* and *acceleration* control. The MCC interface also allows for incremental optical encoders that provide both position and velocity informations. The MCC's provide memory-mapped I/O by allowing indirect access to Command/Response Buffer and various control and status registers. All *commands* and *requests* are transmitted via these registers.

3.3 Software

The MOSAIC/ED I[3,5] software system is composed of two components: (a) **frontend**: comprising of a C programming system with access to C library routines that perform various actuation and sensing operations; and (b) **backend**: a `VxWorks`$^{\text{tm}}$ based real-time system that implements the actuation and sensing operations.

The MOSAIC/ED1 system can be programmed in a high level language such as C or Pascal, where the low-level actuation and sensing operations are accomplished by a set of "library" calls. The real time operating system `VxWorks`$^{\text{tm}}$ handles the synchronization of and mutual exclusion among various low-level operations via internal queues and semaphores and thus provides the user the illusion of smooth concurrent operations of the axis actuators and the sensors; additionally, it ensures that these operations are executed in a timely manner.

Figure 1: **NYU Undergraduate Teaching Laboratory.**

2 Objectives

The ED I robot system was designed with several goals in mind:

- Firstly, the system was required to be simple and inexpensive in order that it could be reproduced and disseminated easily—with the cost going down with each reproduction process.

  The simplicity of the system was achieved by chosing the arm to be based on the *direct-drive technology*. Each joint (altogether four) itself is a motor without any complicated transmission or coupling mechanism. Each of the main links (altogether two) is simply an aluminum hollow rectangular tubing with the ends being motor mounts that provide adaptive connections.

  The kinematic structure is based on the standard SCARA architecture, which simplifies the kinematics and dynamics considerably as the main component of the arm is just a two-link planar kinematic chain. The actuators are also so chosen that the control laws are not too complicated. The only sensors that are currently available are the position sensors (encoders) already integrated with the motors and easily accessible via the motion control hardware.

- Another important design goal was to make the robot system flexible (i.e., multi-functional) by allowing for several attachments and integration of other devices. For instance, the system can be easily modified to act as a manufacturing cell with addition of chucks, fixtures and x-y table (with a pan-tilt mechanism). Also, cameras can be easily attached to the arm itself and the rudimentary visual information can be used by the controller.

- Last but not least, the robot system was designed to be safe for even novice users. This goal was to be achieved without sacrificing the system's ability to be used in heavy industrial applications. Thus, the safety was achieved not by down-scaling or under-powering the entire system, but by providing layers of protective mechanisms.

3 Laboratory Design and Construction

3.1 Mechanical Hardware

ED I is 4 degree-of-freedom robot arm with SCARA like architecture. The main links—shoulder, θ_1 axis, and elbow, θ_2 axis—form a planar kinematic chain. At the end of the second link, the z axis provides a linear actuator to move the end-effector in the vertical direction and the distal joint, ρ axis allows the end-effector to be oriented at any angle.

The θ_1 and θ_2 joints are actuated by two Yokogawa direct-drive AC servo motors with very high torque as well as high accuracy capabilities. The motor housing is connected to one end of the preceding link (or base) and the armature is directly connected to one end of the succeeding link. There is no additional coupling or transmission mechanism. The motors for the joints have built-in encoders which provide the positional sensor-values directly.

Abstract

The primary goal of the NYU educational robotics project (NYU-ED) is to create a disseminable, multi-functional and inexpensive laboratory course sequence, aimed at improving the practical skills of undergraduate students specializing in robotics, vision, AI and manufacturing disciplines.

The earlier approaches to robotics laboratory education have been to use either industrial robot arms or commercially available low-power arms. In each case, there have been considerable problems in the lack of an ideal interface, in not providing enough flexibility to add other devices, or in the absence of adequate safety. Also, the underlying dynamical model is usually so complicated that performing any control experiment has been beyond the scope of all but advanced graduate students.

In this report, we describe our approach to deal with these problems in constructing a modern robotics laboratory. The main work-horse of the NYU educational project was chosen to be a multi-functional ED I robot system, consisting of a 4 DOF DD arm and several auxiliary devices. The system was designed to be simple, inexpensive, flexible and safe.

We also describe our experience with some advanced laboratory experiments using miniature direct drive robots that have proven to be ideal for teaching as they are reconfigurable, safe and easy to program.

1 Introduction

In the spring of 1990, we initiated an educational project at NYU, whose primary goal was to create a disseminable, multi-functional[1] and inexpensive laboratory course sequence, aimed at improving the practical skills of undergraduate computer science students specializing in robotics, vision, AI and manufacturing disciplines.

Our motivation to build such a laboratory arose primarily from our desire to provide students with the practical experience to complement their understanding of the principles involved in robotics, automation, AI and manufacturing sciences. In the past, most of the research in robotics was motivated by simple applications using industrial robot arms suitable for routine welding, spray-painting and part-assembly operations. At the time we initiated this project, there were few universities with regular robotics courses aimed at undergraduates; where a standard introductory course existed, students typically regarded a robot as an open kinematic chain, having a straightforward kinematic and dynamic structure. The accompanying laboratory training typically involved only the programming of a commercial industrial robot to perform simple 'pick-and-place' tasks.

Thus, we felt that there was an acute need for robots suitable for the more extensive educational purpose. To achieve this goal, we proposed to build an 'educational robot' with a structure, which is simple and yet easily modifiable for the multiple functions it may have to serve.

In this paper, we shall describe the robot and our experience with the undergraduate course "Introduction to Robotics" taught by the first author.

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[1] The proposed laboratory is multi-functional in the sense that the same laboratory may be used for more than one area: AI, vision, robotics, real-time systems, manufacturing, for instance.

NYU Educational Robotics Project: A Pedagogic Overview [*]

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