Appendix: B
A Proposed Course Sequence

B.1. Basic Robotics

This is a junior/senior level introductory course, covering the fundamental concepts of robotics and aimed at students from computer science, engineering and mathematics departments. 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. ([2, 4, 5, 7, 22, 24, 31]). Prerequisites are introductory calculus, basic linear algebra and moderate experience with high level programming languages.

The following is a suggested list of experiments for this course; each takes about two weeks. (Also see §4).

- **Experiment 1: System Familiarization and Robot Kinematics**.
  Students are introduced to the system, consisting of the robot, its actuators, its control units, the interface and the computer system. A description of the functionality of the system (via flow-charts) is presented, followed by a discussion of the safety rules and the conduct in the laboratory. A demonstration of the subroutines to read feedback signals and to command joint movement of the robot.

  (1) Students are asked to define the coordinate frames for the joints of ED I, to identify the Denavit-Hartenberg parameters, and using these D-H parameters, to compute forward kinematics and manipulator Jacobian. (2) Next they are asked to conduct an experiment to identify kinematic singularities by moving the robot few times, each time coming close to the singularities. Finally they are asked to experimentally verify the non-commutativity of rigid motions.

- **Experiment 2. Inverse Kinematics and Trajectory Generation**.
  (1) Students are asked to develop a software package capable of moving the object in the task-space. This involves combining inverse kinematics with some simple interpolation techniques (e.g. cubic polynominals method or straight line with parabolic blends method). Each student program is tested by writing the figure eight (∞) with a marker. (2) This is followed by several other simple path planning experiments.

- **Experiment 3. Control of Simple Mechanical Systems**.
  (1) Students are asked to derive an *exact* model of the actuator (a D.C. torque motor), located at the last joint and loaded by the last link. Simplification of the model by appropriate approximations is allowed. Students then compare the approximate model with the exact model. (2) Next, they experiment with and compare proportional (P) and proportional-and-derivative (PD) feedback controllers, designed for the position control of the last joint (e.g. the robot's response to a step input signal).

- **Experiment 4. Robot Arm Dynamics and Control**.
  (1) 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 $\frac{1}{3}$ of maximum joint velocity, $\frac{1}{3}$ to $\frac{2}{3}$ of maximum joint velocity and $\frac{2}{3}$ to 1 of maximum joint velocity). (2) Next, they design, implement and compare position control algorithms, using following two approaches: *joint-space control* and *task space control*.

- **Experiment 5. Interfacing with the External World: Force Control**.
  The main objectives are to study (1) force control with fixed contact and (2) hybrid position/force control. First, the students design and implement a simple feedback control algorithm that tracks a desired force trajectory in the normal direction, while stabilizing a fixed point of contact between the tip of the robot and a fixed surface. Next, they design and implement position/force control algorithms, where the tip may be allowed to move on some surface of constraint.

- **Term Project.** After consulting with the instructor, the students may choose a topic for their term project. They are asked to read one or two research papers in the area of their choice. Possible topics include (1) contact motion and force control, (2) coordinated manipulation by two robot arms, (3) dynamics and simulation of a one legged hopping robot using simulation and graphics tools, (4) motion-planning with obstacle avoidance and (5) planning and execution of a simple task.

B.2. Intermediate Robotics

This is a senior/first year graduate level course covering concepts and methods underlying current research in robotics: geometric approaches to manipulator kinematics, contact kinematics and grasp kinematics of a robotic hand system; dynamic models of, and linear and nonlinear control techniques for, robotic hands, space robots and legged locomotion robots; algorithmic approaches to motion planning for robotic manipulators and mobile robots, subject to holonomic and nonholonomic constraints. ([15, 24, 26, 27, 28]). Accompanying the lectures are four laboratory experiments designed to aid the students in mastering the principles and techniques.

- **Experiment 1. Kinematic and Dynamic Modeling of a Two-Robot Manipulation System**.
  Two robots (in our case, ED I and an IBM SCARA robot) are integrated to form a *two-fingered robotic hand system* which performs a coordinated manipulation task, such as moving a box on a circular trajectory. Using position, velocity and force sensors, students are asked to determine the kinematics of the *two-fingered robotic hand*, including the contact models, hand Jacobian, grasp map ([9, 15, 24, 35]) and the kinematics of contact ([28]).

- **Experiment 2. Coordinated Manipulation.**
  Using the hand kinematics of the previous experiment, students are asked to implement and evaluate the dynamic coordinated control algorithms ([30]), the master-slave control ([23, 34]) and the PD type control algorithms ([2, 17]).

- **Experiment 3. Path Planning with Obstacle Avoidance.**
  Students are asked to implement the Schwartz-Sharir motion planning algorithm on the 3-DOF planar arm amidst obstacles. Also see [22].

- **Term Project.** The term project consists of a well defined research problem. After consulting with the instructor, the students are asked to choose a topic, analyze the problem and then propose a possible solution. Finally, they proceed to experimentally test their solution and give a presentation of their results. The list of topics include: (1) robust coordinated control algorithms for a two-fingered robotic hand, (2) motion planning for a two-fingered robotic hand, (3) hand-eye coordination, and (4) simulation studies of legged locomotion robots or space robots.

B.3. Computer-Aided Manufacturing, CAM

This is a junior/senior level course aimed at familiarizing computer science students with future manufacturing technologies. The topics covered in the laboratory are: computer-aided design, simulation, control, sensors, and quality control. The course is designed to emphasize the computer science skills of the undergraduate students with the engineering components being taken care of by the laboratory technicians.

- **Experiment 1. Computer-Aided Design Methodologies.**
  Students are asked to design a component of their choice on a computer-aided design system (e.g. the Anvil 5000 software package). Using this system, students can create their components in wire frame images, with boundary representations, and, to a limited extent, using constructive solid geometry. This experiment will familiarize the students with basic design methods, the operation of computer-aided design systems, and, simultaneously, with standard graphics interface languages (e.g. IGES and PDES).

- **Experiment 2. Manufacturing Simulations and Tool Path Generations.**
  In the second experiment, the students are asked to generate a software simulation of a simple manufacturing process, building on their computer-aided design work. In the process, they become familiar with technology that creates tool path simulations on their design. They are then introduced to a simple expert system, running in the local CAD/CAM environment that advises on the usable set-up procedures and operating instructions. Via simulation, they can then see how their particular part can be made on a full scale CNC machining center and turn into the component ready for use in steel or aluminum.

- **Experiment 3. Simple Manufacturing Technologies.**
  Using the ED I robot arm, the students are asked to create plastic hard copies of the components that they have designed and simulated in Experiments 1 and 2. In the laboratory, the students use prototyping wax as the component and limit their operations to two-dimensional routing on the wax. They are then able to program the ED I robot arm to carry out the two-dimensional cutting operations and create the outer profile of their desired part. In addition, other small cutting tools are supplied as an ancillary to the robot and the students can drill holes and carve lettering onto their components. In this way, they become experienced in the complete CAD/CAM loop even though these experiments are only carried out in simplified shapes and with the prototype wax.

- **Experiment 4. Force Position Control.**
  In this experiment students are made familiar with a simple grinding operation as an example of carrying out manufacturing operations that require both force and position control. For this experiment, the ED I robot is equipped with small finish grinding tools and the students are asked to smooth an arbitrarily rough contour. They are required to program the robot to the coarse profile of the object and then grind the surface smooth. Thus, they demonstrate position control along the direction of the profile and force control normal to the profile in order that the grinding tool presses against the surface with uniform load. This experiment overlaps with the Experiment 5 of *Basic Robotics*, but extends the students' understanding of the importance of such force control in manufacturing processes.

- **Experiments 5 & 6. Sensor Based Manufacturing.**
  As a final development of experiments 5 and 6, a rudimentary two-dimensional vision system is used to inspect and measure the components that the students have manufactured and ground smooth. Students can acquire appreciation of different lighting methods for computer vision and manufacturing, the available technologies in terms of CCD cameras and lenses, and they, thus, gain experience in the general set-up of industrial sensors. As the laboratory is developed, it may be possible to use the vision information as a feedback to the system and to make corrections in the grinding part and in the routing trajectories. The overall goal of this last experiment is to make the students aware of quality control methods in industry.

B.4. Real Time Systems

This is a junior/senior level introductory course, covering the principles, implementation and applications of a real-time system. The topics covered in the course include: hard-real time constraints; periodic and aperiodic tasks; operating system issues: scheduling, communication, critical sections, priority inversion problems; real time system modeling: petri-nets, temporal logic, discrete event systems; real-time operating systems and languages; applications to robotics (with examples such as controlling a pin-ball machine or a juggling robot). The text by Levi and Agrawala covers most of these topics [21]. Prerequisites are basic robotics, introductory operating systems and moderate programming experience.

The following set of four experiments are to be conducted, with each experiment taking roughly three weeks. Additional term projects may be assigned, and will usually involve building real time controllers for an integrated robot system (e.g. a pin-ball machine, four-finger manipulator, the Utah/MIT hand or the NYU manufacturing system).

- **Experiment 1. Cyclic Executive.**
  The students are asked to implement a simple cyclic executive system in C programming language, capable of handling the proportional (P) and proportional-and-derivative (PD) control schemes for the ED I robot.

- **Experiment 2. Periodic Tasks.**
  In this experiment the objective is to model the sensor, actuator and data-logger servo tasks for the ED I robot controller as simple periodic tasks with different periods. The students are asked to implement the controller, by using a simple rate monotonic scheduler and then evaluate the performance as the periods of the tasks are uniformly scaled.

- **Experiment 3. Sporadic Tasks.**
  The students are asked to model the sensor, actuator and data-logger tasks for the ED I robot controller as aperiodic tasks with given minimum separation times and hard and soft real-time constraints. Additionally, each task may be given priorities, based on certain value-functions associated with the tasks. Next, they are asked to implement the controller, by using a variety of scheduling schemes, e.g. earliest-deadline-first, least-laxity-first, etc. and then evaluate the performance under different scheduling schemes and as the system is made overloaded [3].

- **Experiment 4. Hierarchical Controller.**
  In this experiment, first the system of two robots working cooperatively is decomposed into several levels of a hierarchical system. The students are asked to implement the lowest servo-level as a system of *periodic* tasks, and the higher levels as systems of *aperiodic* tasks. The communications between the successive levels are to be implemented via double-buffers. Finally, the students evaluate the performance of the system.

B.5. Computer Vision

The proposed course is for juniors or seniors, and covers the fundamentals of computer vision and image processing. The course covers standard topics in image sensing, processing, and analysis, stressing algorithmic methods, as is typically covered in an introductory image processing and computer vision class. Recent texts (e.g. Schalkoff's book [33]) make it possible to cover topics in an accessible and rapid fashion, affording the students the option of implementing basic techniques in a suitably equipped laboratory. The course covers image formation and color theory, feature extraction, image enhancement, some signal processing theory, image segmentation, multiresolution image analysis, motion, stereo, pattern recognition and labeling, and model-based vision. Lectures and readings are used as guides to the projects and experiments that students will conduct on hardware and software tools integrated with the usual computing facilities available.

There will be four assigned experiments to supplement the first eight weeks of the course, and then an assigned term project chosen from a list of proposed projects, envisioned to encompass the last six weeks of the course. The proposed projects are as follows:

- **Experiment 1. Software Introduction.**
  The students are asked to demonstrate capability of acquiring digital imagery, running edge detectors and feature detectors, running convolutions and simple nonlinear enhancement processes, and programming in high-level vision application software. Supplied software enables interactive execution of individual image operations, so that only embodying scripts must be supplied by the students. These scripts, written in C, are used to build up a library of routines.

- **Experiment 2. Image Restoration and Reconstruction**
  Students are supplied with several images that have been subjected to degradation through manipulation and noise. The task is to undo the degradations, recording the steps. Examples of degradations that the students will have to contend with is blurring, grayscale changes, image rotation, line drop-outs, additive noise, and scanline variations.

- **Experiment 3. Multiresolution image analysis.**
  In this experiment, students are asked to perform an image analysis task, such as edge or feature extraction, or simple model matching, using a multiresolution image representation. The students develop scripts to perform these functions and they have to contend with issues related to reasoning about the choice of scale and combination of information from multiple scales.

- **Experiment 4. Stereo matching.**
  Stereo pairs are provided, and students are asked to implement any of a number of stereo matching algorithms in order to obtain depth estimates to object points visible in both images. Candidate algorithms include iterative disparity analysis, the iterative Marr/Poggio algorithm, zero-crossing feature matching, branch-and-bound search for feature matching, and Cepstral filter matching. Ground truth of actual object depths are provided.

- **Term project.** Each student is expected to implement a substantial image analysis system in the software environment provided, using a research paper or other published description as a guide. Example projects include image segmentation methods based on color and/or texture, motion extraction from image sequences, texture analysis or depth-from-texture studies, generalized Hough transformation studies, geometric hashing for object recognition, or comparative feature analysis.

B.6. Artificial Intelligence and Learning in the Robotic Setting

This is a junior/senior level course concerning a variety of topics in artificial intelligence, which bridges the theory, artificial intelligence and robotics areas. The topics to be covered include machine learning from examples, neural networks, and applications to vision, robotics and manufacturing. The course aims to allow students who have a solid mathematical and theoretical foundations with ways of applying such theoretical principles to robotics-related problems in artificial intelligence. This course includes the following machine learning experiments to be undertaken in the robotics educational laboratory.

- **Experiment 1. Learning on Disc Throw, I**.
  A round disc is put in a holder fixed on the end of the robot arm, which is initially positioned at a fixed place. The students are asked to design a series of continuous movements of the robot arm with adjustable parameters so that the arm will throw the disc to a position as close as possible to a bar, but without touching that bar. Then the student should adjust the parameters to accomplish the job through experiments.

  The student should also design a learning procedure for the machine so that the machine can determine these parameters automatically through experiments. The result of an experiment, which is input to the learning algorithm, can be a real number representing the error.

- **Experiment 2. Learning on Disc Throw, II**.
  The students are asked to develop an automatic learning procedure for the case that the initial position is an arbitrary one. The initial position is input to the computer. They are also asked to design an automatic learning procedure to play a match with a human player so that the winning probability of the robot arm is maximized in the asymptotic limit.

- **Experiment 3. Monitoring a Moving Object**.
  A stick is fixed upwards on the end of the robot arm. A bright sign is fixed on the top of the stick and monitored by a camera. A person holds another sign which is also monitored by the camera. The students are asked to develop a fast algorithm to determine the positions of these two signs and to control the motion of the robot arm so that the sign on the stick always follows the other sign which is randomly moved by the person.

- **Experiment 4. Stick Balancing**.
  A stick is connected to the end of the ED I robot arm by a linkage which allows it to fall down along two opposite directions. A bright sign is fixed to the top of the stick and monitored by a camera. The students are asked to design a neural network program to control the robot arm so that the stick will not fall. The student should also design a program to balance the stick so that the stick always follows a bright sign which is randomly moved by a person.

B.7. Linear and Nonlinear Systems

This course is offered to junior/senior undergraduate and/or first year graduate students from the mathematics and the computer science departments, and makes extensive use of the robotics educational laboratory to teach basic principles and related design techniques in linear and nonlinear systems.

The syllabus includes: modeling of linear time-invariant(LTI) systems, linear differential equations, Laplace transform techniques, transfer function description of input-output system, feedback control and compensator design; transient response analysis; modeling and description of nonlinear dynamic systems, differential equations, critical points and Lyapunov stability analysis; control techniques for nonlinear systems.

- **Experiment 1. Modeling of a D.C. Torque Motor**.
  Students are asked to obtain a model of the D.C. torque motor which drives the last joint of the ED I arm, simulate the transient response of the model and finally, compare the results with the experimental results. Finally, they evaluate the accuracy of the model.

- **Experiment 2. Controller Design**.
  Students are asked to design a proportional (P), proportional-and-derivative (PD) and lead-lag compensator for the D.C. torque motor model. Next, they evaluate the performance of the compensator using a step response.

- **Experiment 3. Modeling and Control of Inverted Pendulum**.
  Students are asked to connect an inverted pendulum to the tip of the ED I arm, obtain a nonlinear system description of the system and then, identify the equilibrium states. Using a nonlinear control law, they stabilize the system in the up-right position.

- **Experiment 4. Adaptive Control of the ED I Robot with Unknown Load**.
  Students are asked to derive the nonlinear dynamic model of the ED I robot arm assuming that the load at the distal point is unknown. Model-based linearization and parameter estimation techniques are to be applied to compute the inertial load. Adaptive techniques are to be used to achieve high-fidelity control[1].

B.8. Undergraduate Thesis Projects

This course is intended to provide senior students the opportunities of pursuing advanced studies in Robotics, AI, CAM and Vision. Under the direct supervision of a faculty member, the students first conduct a literature survey in the area of their interest. Then, they choose a more focused problem, propose a feasible approach and implement the approach on a testbed consisting of ED I robot, a vision sysytem and several manufacturing tools. A number of possible topics for thesis projects include, but are not limited to, the term projects outlined in the set of courses listed in the earlier subsections.