An Undergraduate Mechatronics Project Class at Philadelphia University, Jordan: Methodology and Experience

Tarek A. Tutunji, Ashraf Saleem, and Saber Abd Rabbo

***Abstract*—Mechatronics is a branch of engineering whose final product should involve mechanical movements controlled by smart electronics. The design and implementation of functional prototypes are an essential learning experience for the students in this field. In this paper, the guidelines for a successful mechatronics project class are presented, evaluated, and discussed. Furthermore, the paper introduces a general mechatronic system design methodology that should equip students to carry out a successful mechatronics project in their undergraduate training. Three student projects at Philadelphia University, Jordan, are examined in detail, with descriptions of their goals, design, and implementation.**

***Index Terms*—Course evaluation, course structure, design methodology, mechatronic systems, student projects.**

I. Introduction

MECHATRONICS education has received much attention in recent years [1]–[3]. Several universities now offer B.S. degrees in Mechatronics Engineering, while others have introduced an undergraduate mechatronics course to their mechanical and electrical engineering curricula. Mechatronics can be defined as the analysis, design, and integration of mechanics with electronics through intelligent computer control. Mechatronics is the field of engineering in which computers are used to control mechanical movements through feedback electronics and sensors [4], [5].

In order for any mechatronics education program to be successful, significant attention needs to be given to student projects. Those projects can be introduced to the students throughout their studies as part of the syllabi of different courses. Equally important, a well thought out senior undergraduate project course must be established. Several researchers have outlined their experience in developing such mechatronics projects [6], [7].

The Mechatronics Engineering Department at Philadelphia University (PU) in Jordan promotes practical undergraduate projects for the students in which the emphasis is on the actual implementation of a complete mechatronic system. Throughout the process, students learn to analyze existing technologies, to understand system functionality, and to design and build products.

In this paper, the experience gained in designing the mechatronics project class at PU will be presented. This description will include the project design methodology, and the material given at weekly classroom seminars, whose effectiveness will be evaluated and discussed. Finally, a detailed account will be given of three successful projects.

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II. Course Objective and Classroom Material

The Mechatronics Department at PU offers a compulsory one-year engineering project that senior-level students take before graduation. The mechatronics staff prepares a list of available projects for students to choose from. Students can also propose their own projects, which may or may not be accepted by the department. The project is divided into two main stages, covering two semesters. During the first stage, students study the theoretical aspects of the given project, which includes their preparing a literature review, a clear project description, a block diagram design, a flow chart design, and a project planning chart. At the end of the first semester, students submit a report that includes all their theoretical work, as well as a simulation and schematic diagrams with the detailed parts list needed to implement the project. In the second stage (i.e., the second semester), students proceed to building their project, which incorporates the mechanical assembly, circuit building, programming, and interface. The project also includes the component, subsystems, and final system tests, carried out at the laboratories. The students then submit their final report, which covers all their project work throughout the entire year.

The main objective of an undergraduate mechatronics project course is for the students to apply their theoretical skills in practice, in order to design and build an integrated engineering system, in a team environment, under time constraints. This experience also includes their developing technical writing and communication skills, through report writing and presentations.

Students work in teams to produce the plans, the design documents, a system analysis, a functional prototype and a final report. The teams give an oral presentation to a jury composed of the project supervisor and two other faculty members. The jury critiques the technical report documentation, the project design, prototype functionality, and solutions developed by the students for each project team member. Each member of the jury separately fills out an evaluation form. The final grade is a weighted average of the three evaluations (with the supervisor and the two other members awarding 40%, 30%, and 30% of the marks, respectively). The grading for the evaluations is divided as follows: literature review (10), technical report writing (20), design and engineering approach/problem analysis (25), prototype implementation (30), and project presentation /conclusions (15).

Some engineering colleges offer their senior project class without allocating class time for lectures. A major drawback to this approach is the potential lack of commitment on the part of the students, who can delay their work until the last weeks of the semester, resulting in a poor quality final project. The Mechatronics Department at PU, therefore, decided to include a one-hour lecture each week in the project class, thus essentially treating it like a regular class. This lecture time is in addition to a student's office meetings with his/her supervisor. The classroom lectures are treated as weekly seminars, in which design methodologies and project management skills are presented to the students, and during which a staff member guides the students in tackling their project work. The seminars also offer students the opportunity to meet the staff and discuss their progress on the project. These lectures were divided as follows.

A. Introduction

Students are introduced to the course structure and philosophy. A general description of all the projects offered by the department is provided, along with discussion of any other projects suggested by the students. Students are then given a two-week period to meet with the staff members in order to choose their projects and supervisors.

B. Mechatronic Systems

A general description of mechatronic systems is reviewed with the students. At this level, students have already been exposed to mechatronic systems at various points during their years of study. However, a general look at mechatronic systems is helpful in order for the students to have a clear grasp of the necessary subsystems and components that together make a mechatronic system.

C. Project Management I

A general description of project planning and management is given. Subjects include planning strategy, team building and group dynamics, conflict resolution, roles and responsibilities, time management, budget allocation, and leadership skills

D. Project Management II

This session is concerned with critical path method and work breakdown. GANTT charts are introduced which help students understand the timing of critical activities, in order to meet their aims and objectives by the deadline.

E. References and Literature Sources

Students are instructed that they should start their project by researching the available literature. They are made to understand that their project needs to have both library and internet reference sources. Students need to compile research notes in order to identify sources of information that are relevant to their work.

F. Design I

Based on the literature survey, students are taught how to convert the original terms of reference for the project into a comprehensive specification of requirements (which covers hardware, software, users, etc.). The specification of requirements can then result in the development of a 'detailed design specifications'. This specification should also identify the needs for every major aspect of the potential design (e.g., materials, structure, environment, size, performance, cost targets, etc.).

G. Design II

Students are taught how to construct detailed design specifications, by means of an example. These design specifications should be comprehensive and written in an understandable form (using diagrams, flowcharts, or other appropriate method). Preparation of a product design specification consists of some primary elements that must be considered before beginning the design; these elements include: (1) performance requirements, (2) operating environment, (3) maintenance, (4) target product cost, (5) materials, (6) quality and reliability, (7) testing, and (8) market constraints.

H. Simulation

The importance of simulation is emphasized to the students. They are instructed to analyze their preliminary designed model by using one of the simulation tools, in order to verify that it meets the given design specifications. Students are advised to perform the simulation before moving on to the implementation and prototyping stage, so that to identify and correct any problems in their initial design. They are normally encouraged to use either MATLAB, Labview, Electronic Work Bench (EWB), or Pro-ENGINEER as a simulation tool.

I. Component Sources

Internet sources are provided for the students, so that they can find the necessary components for their projects. Several data sheets are presented and explained, to teach students to understand component requirements and specifications. Also, students are given a list of local vendors, from whom they can obtain both new and used parts.

J. Troubleshooting Skills

Troubleshooting techniques used in the labs for electronic component and subsystem testing, using scopes, multimeters, and function generators, are reviewed with the students.

K. Technical Writing

The expectation for the project report are described, including coverage of how to write an abstract, a conclusion and how to organize figures and tables. The students are trained to prepare a brief project document at the end of first semester. This 20–30 page document should include a project title, introduction (including aims and objectives), initial design (including block

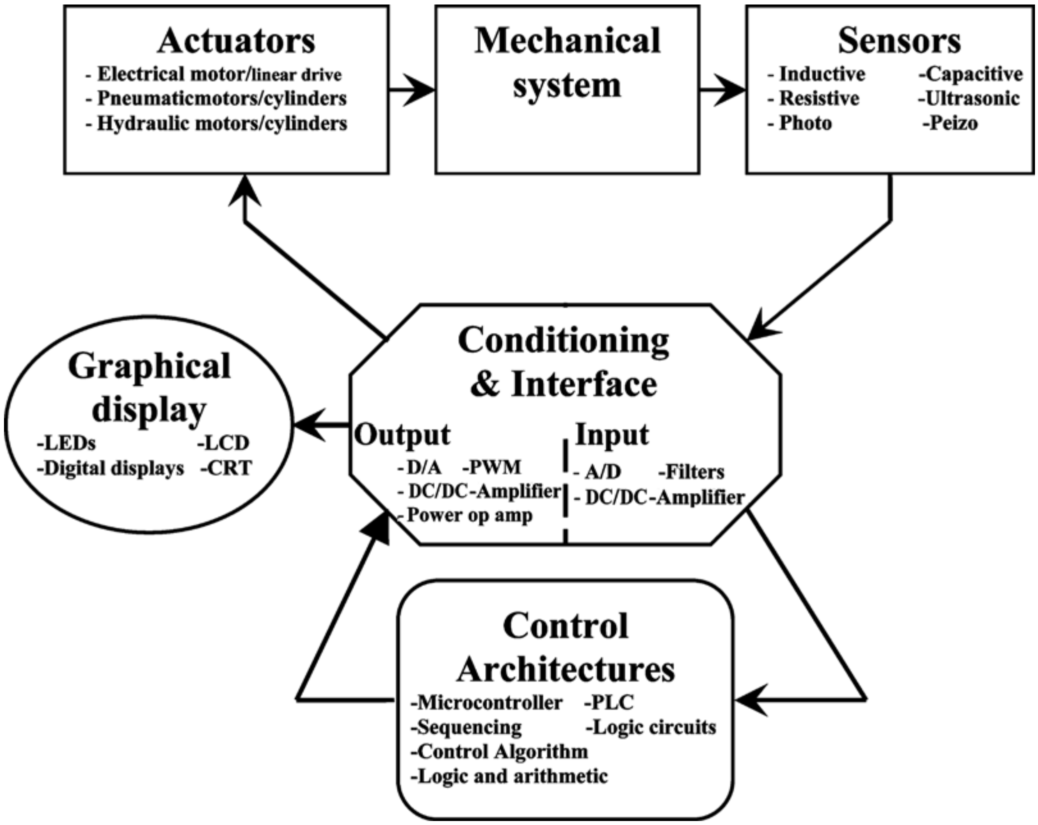

Fig. 1. Block diagram for a general mechatronic system.

diagram, flow charts, and power requirements), design specification, methodology/project plan, simulation, summary/conclusions, references, and appendices.

The final report, at the end of second semester, is a 40–50 page document which builds on the above outlines and adds details of the implementation, experimental work, and results analysis.

L. Presentation Skills

Students are given pointers on how to improve their communication and presentation skills. Students are expected to make a total of four presentations over the one-year project.

III. Design Stages

The process of engineering design is not universal, and therefore might vary between different schools of thought [8]–[11]. However, the following six steps serve to summarize the engineering design process: specify the objective, propose solutions, decide on a solution, analyze and design, implement, and evaluate performance

A mechatronic system is an integrated engineering design, which can be complex to design and optimize since it covers several engineering domains, as shown in Fig. 1.

Optimizing each part separately might not result in the best design. Mechatronics design uses component modeling and simulation in order to establish the optimal tradeoffs between the mechanical and electronic subsystems.

The design stages, which embed the six steps described above, are as follows.

A. Stage 1: Define the Objective and Specifications

1. Identify a problem;
2. Research and propose solutions;
3. Set the initial system specifications.

B. Stage 2: Analyze and Design

1. Establish a general block diagram and a flow chart;
2. Specify the inputs and outputs of the system and therefore choose the appropriate sensors and actuators;
3. Concurrent/Synergistic Design
   a. Design the mechanical frame/machine;
   b. Design the electronic system;
   c. Design the software/controller;
   d. Design the interface between all its components;
4. Model and simulate the system.

C. Stage 3: Build and Test

1. Emulate the controller hardware;
2. Build prototype, test, and evaluate (modify if needed).

The flow chart in Fig. 2 illustrates the steps for the design methodology of mechatronic systems. As seen in the figure, if the prototype does not meet the specifications, then the designer might need to go back to the initial design stages in order to build a revised prototype. It is worth noting that, because of the time limitation for the student projects (one year), once the prototype is built, students rarely make significant modifications to the design, but rather try to have the best possible product by either changing some components or adapting the control strategy.

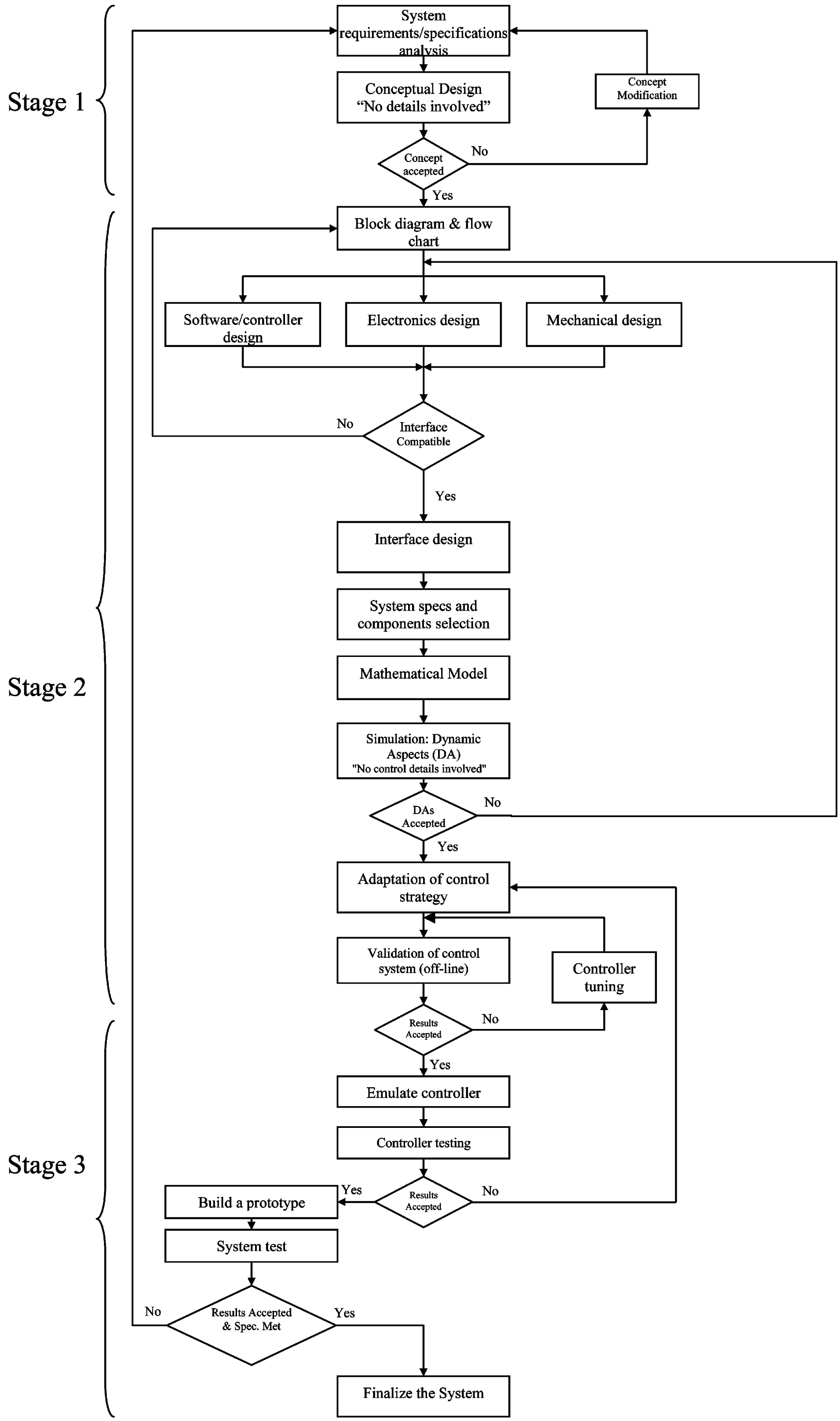

Fig. 2. Design methodology flow chart for mechatronic systems.

IV. Course Evaluation and Effectiveness

Seminar class time was allocated to this course, in order to help the students focus on the course objectives, and to improve the learning outcomes. Shortcomings of projects carried out in previous courses included poor report writing, inadequate presentation skills, miscalculated time management, and errors in the design strategy. Many students did not follow the design procedure steps of formulating sound mathematical models. Others

TABLE I
COMPARISONS BETWEEN TWO PROJECT GROUPS

	Literature review	Technical Report Writing	Design, Engineering Judgment and Problem Analysis	Prototype Implementation	Project Presentation And Conclusions
Group A	66%	41%	58%	50%	58%
Group B	84%	76%	69%	76%	84%
% improvement*	**27%**	**85%**	**19%**	**52%**	**44%**

* % improvement is (group B – group A) / group A

TABLE II
STUDENT EVALUATION OF SEMINAR CLASS

Overview of mechatronic system	3.64
Project management	3.00
Literature sources	3.41
Design	3.64
Simulation tools	3.29
Components Sources	3.88
Troubleshooting skills	3.88
Technical writing	4.29
Presentation skills	3.94

did not simulate the models; instead, they used a trial-and-error method of direct implementation. This approach resulted in either nonfunctioning prototypes, or functioning prototypes that did not meet the specifications.

Table I shows a comparison between the grades of two groups of projects in two consecutive academic years. Group A includes 12 projects completed without the seminar classes while group B includes 13 projects completed with the addition of seminar classes. The percentages indicate the proportion of students who earned an adequate grade (grade C and above) for each criteria. The table shows a clear improvement in all criteria, particularly in technical report writing and prototype implementation.

A sample of 17 students were asked to evaluate the importance of the given criteria (the seminar subjects) to the course objectives, on a scale rating between 1 (lowest importance) and 5 (highest importance). Table II shows the average of their results. It can be noted that, from the students' perspective, all the seminars were beneficial to their project work (i.e., all scored above 3 from 5).

In order to evaluate the quality of the course seminars, a Quality Function Development (QFD) chart was developed as shown in Table III. The table shows how the classroom material meets the course objectives discussed in Section II. The importance rating of the objectives were related to the course grading scheme, while the relationships between the classroom material and objectives were set by the department staff.

Table III shows that the design, simulation, and troubleshooting seminars have the most impact on achieving the course objectives. Specifically, these seminars make a large contribution to the design, engineering judgment, and problem analysis which had the lowest improvement as shown in Table I. Therefore more time should be allocated for these seminars. Furthermore, additional seminars should be introduced to improve students' skills in commissioning systems, so as to improve the quality of the final prototype. In other words, students should be encouraged to test components and subsystems before moving to the final system test. These additional seminars should address: system synthesis (which includes set-up inspection, first run inspection, and system maneuver inspection) and testing/balancing (which requires that all elements are not only working correctly individually, but also working correctly as a composite system).

To meet the above requirements, it is felt that the course seminars should be extended over two semesters, instead of merely one. In a two-semester model, the seminars that cover literature review, project management, design, simulation, component sources, presentation, and technical writing would be given in the first semester, while troubleshooting, system synthesis, testing and balancing seminars would be given in the second semester.

V. THREE PRACTICAL PROEJECTS

In this section, three student projects will be presented, and the design process carried out for each project will be explained. Note that although the design steps might vary slightly among the different projects, they nevertheless follow the general guidelines given in Section III.

A. Clamp Robot Manipulator

This project was to design and implement a pick-and-place pneumatic robot. The robot was composed of three pneumatic cylinders, six valves, one capacitive sensor, and six magnetic sensors. The controller circuit used was based on a PIC microcontroller interfaced with power drive circuits. The pneumatic robot block diagram is shown in Fig. 3.

Fig. 4 shows the pneumatic circuit of the system used. Three double-acting cylinders were used for the x axis, y axis, and end-effecter gripper. Six on-off directional valves were used in order to control the motion of the three cylinders. A total of seven sensors were used: one capacitive sensor to detect the object to be picked, four magnetic sensors for detecting the positions of cylinders A and B, and two magnetic sensors for the gripper cylinder.

The system model was built under Matlab/Simulink in order to simulate the dynamic behavior of the anticipated system. Fig. 5 shows the system block diagram under Simulink for Cylinder A (x axis cylinder), while Fig. 6 shows the position and speed response of the simulated model. The input to the valves was a pulse with variable duty cycle.

The physical system built is shown in Fig. 7.

TABLE III
QFD CHART FOR PROJECTS COURSE

Importance Rating:
1 = Low Importance
3 = Moderate Importance
5 = High Importance

Relationships:
9 = Strong
3 = Moderate
1 = Weak
0 or Blank = No Relationship

		Importance Rating	Classroom Material: Overview of mechatronic systems	Project manegement	Literature Sources	Design	Simulation tools	Components sources	Troubleshouting skills	Technical writing	Presentation skills
objectives	Literature review	1			9						
	Technical report writing	3			1					9	2
	Design, Engineering thinking, and problem analysis	4	3	2	2	9	7	2	3		
	Prototype implementation	5		5		7	4	5	7		
	Project presentation and conclusion	2								3	9
	Raw score		12	33	20	71	48	33	47	33	24
	Relative %		4%	10%	6%	22%	15%	10%	15%	10%	7%

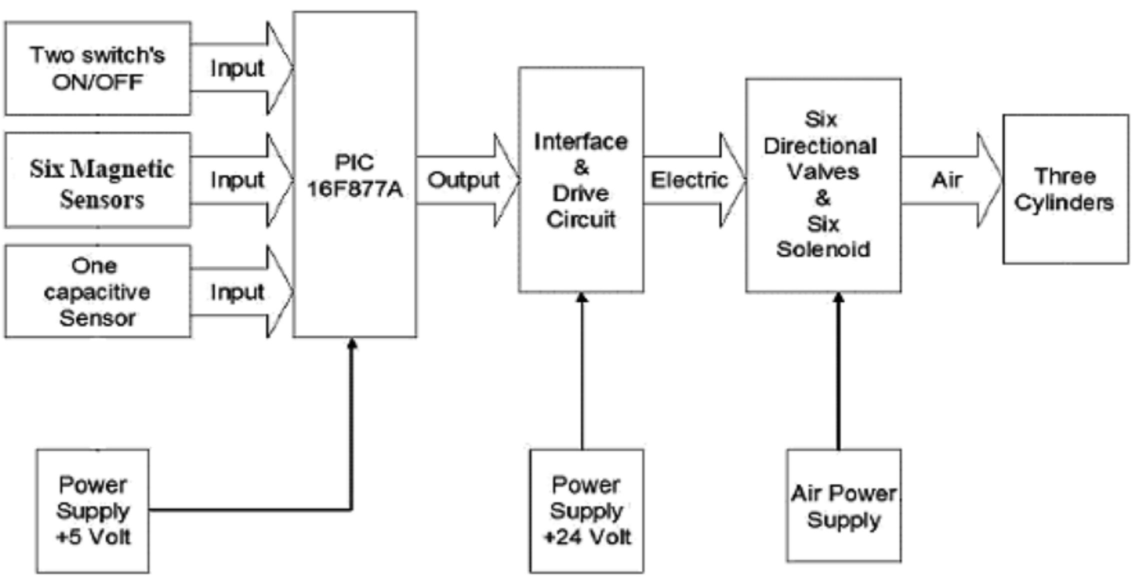

Fig. 3. Block diagram for the pick-and-place pneumatic robot.

B. Mechatronics Education Kit

The objective of this project was to design and build a mechatronics education kit that could be used for a set of laboratory experiments by the students. Staff members identified the need to build such kits in-house, and, therefore, to establish local expertise in developing lab equipment.

The specifications were written such that the kit should perform three basic control experiments: dc motor direction and speed control, stepper motor position control, and temperature block control. In the initial design stages, the block diagram was constructed as shown in Fig. 8.

The main components used were: a dc motor circuit (series-shunt 12-V,1A), H-bridge driver/rotary encoder with photocoupler, stepper motor circuit (4-step 3 V stepper motor, and Darlington driver), and temperature circuit (LM35 temperature sensor, 12-V fan, relay, power resistor as heater, and opt couplers).

The main unit used a 9-keypad and an LCD display. The total number of inputs needed for the microcontroller were 9 (1 temperature (analog) + 1 encoder + 7 keypad) and the total number of outputs were 15 (1 fan + 1 heater + 4 stepper motor + 2 ac motor + 7 LCD).

In order to run any of the three experiments, the user would make the appropriate connections between the sub-systems and the main unit, and then enter the experiment number using the key pad. The output result (such as the temperature value, motor position and speed) would then be displayed on the LCD.

The control methodologies for the three experiments were set to be: Pulse Width Modulation for the dc speed control, open

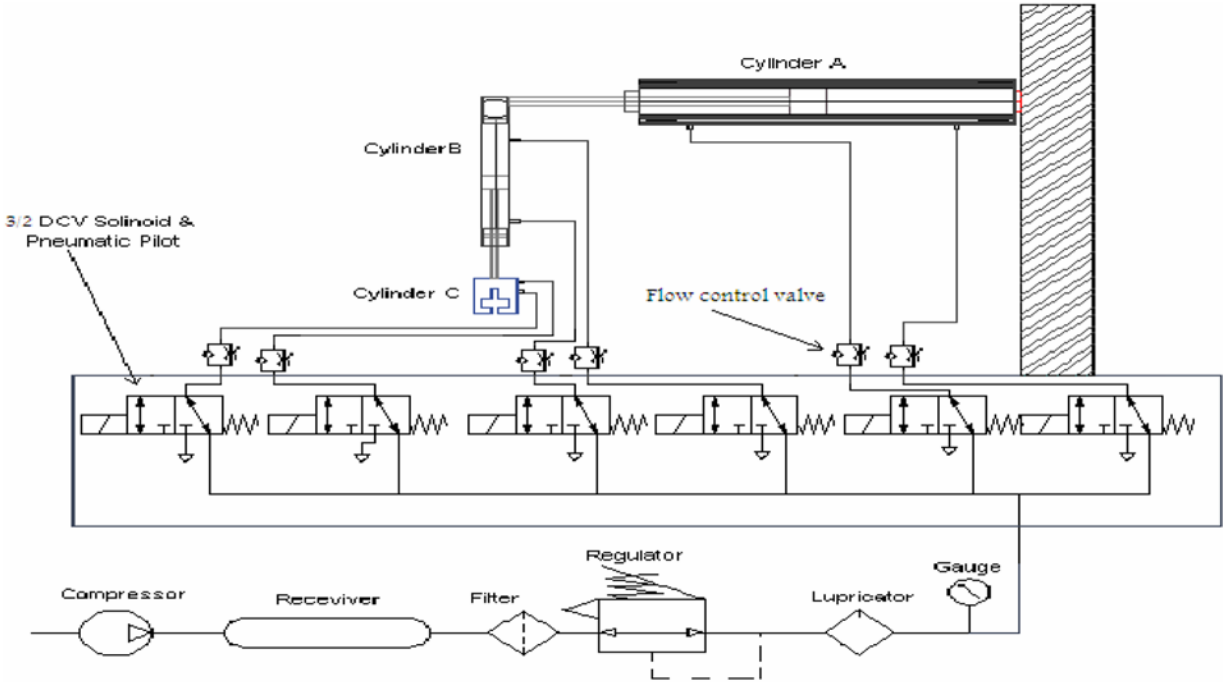

Fig. 4. Pneumatic circuit of the system.

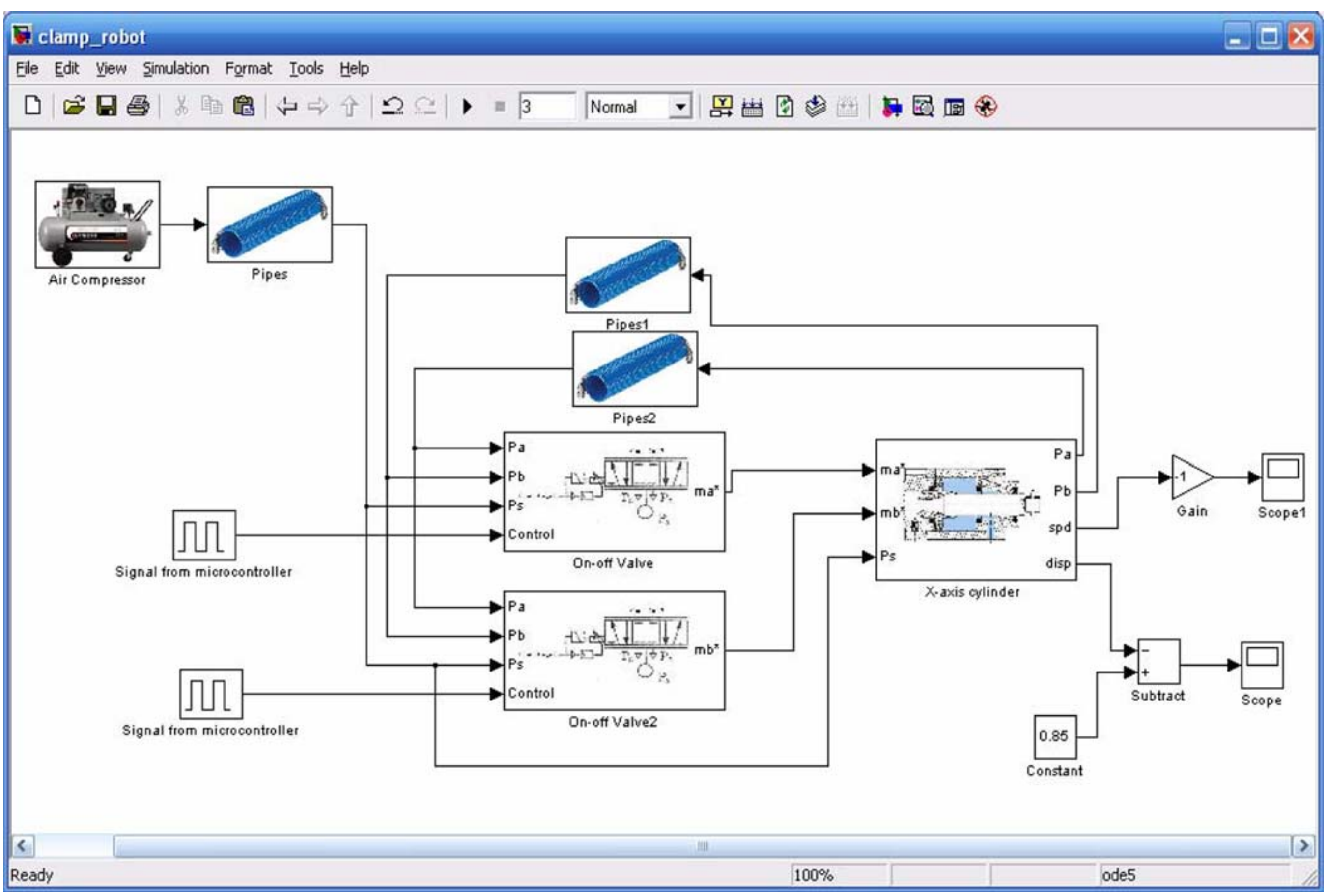

Fig. 5. Simulink block diagram for cylinder a in the clamp robot.

loop step control for the stepper motor position, and on/off control for the temperature block.

The PIC16F877 microcontroller was chosen because it is easy to program and interface, can handle 33 I/O signals (in-

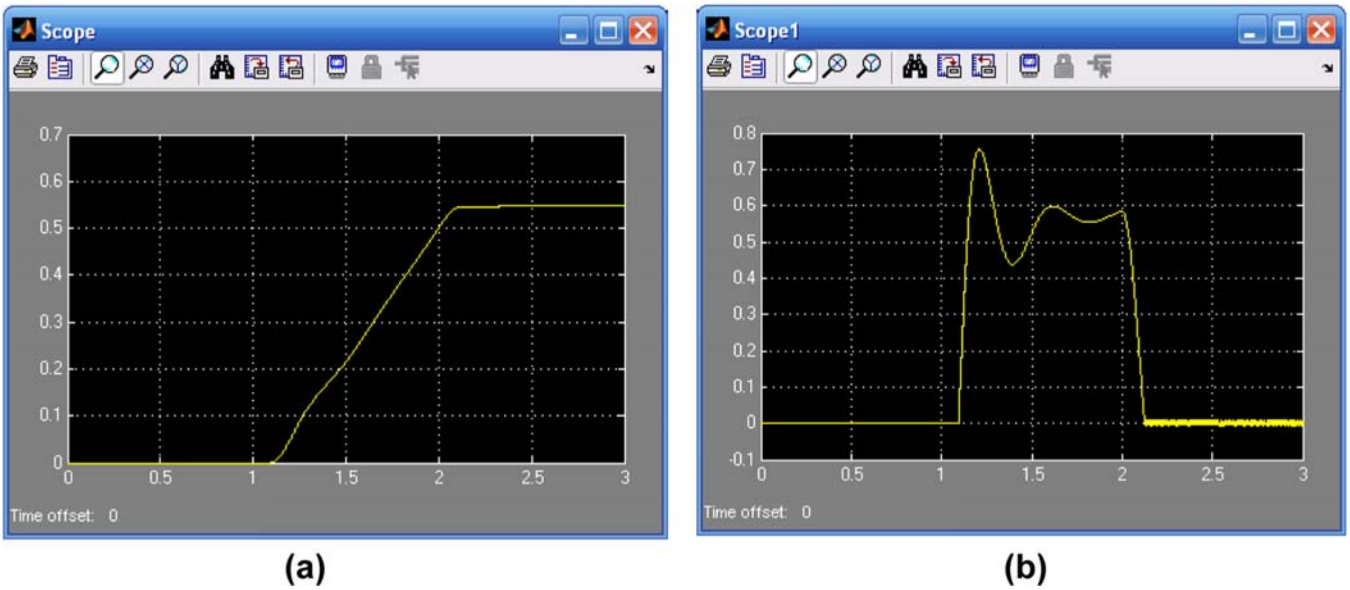

Fig. 6. Simulated response of cylinder a for the clamped robot project (a) displacement, (b) speed.

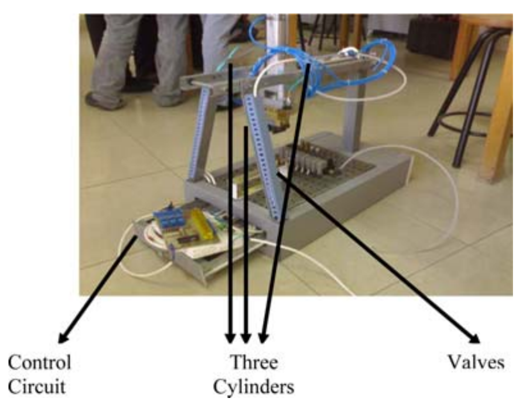

Fig. 7. The completed pick-and-place pneumatic robot built.

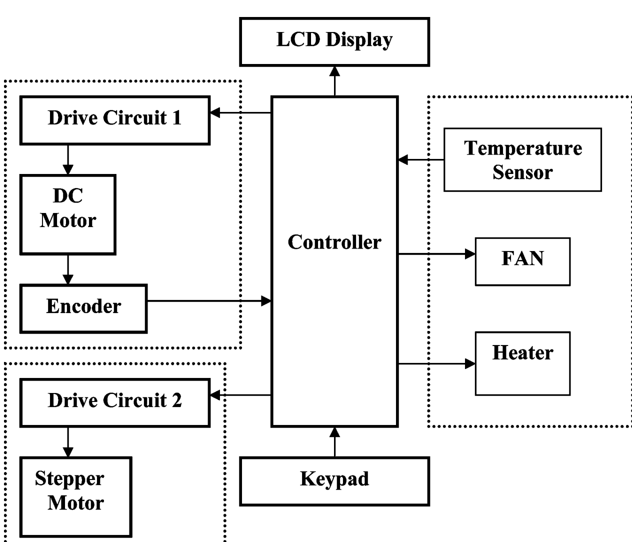

Fig. 8. Block diagram of the mechatronics kit.

cluding analog ports), and contains a PWM counter. Simulation of the PIC program was carried out using Matrix Multimedia Software. The simulation results are shown in Fig. 9 and the final prototype product is shown in Fig. 10.

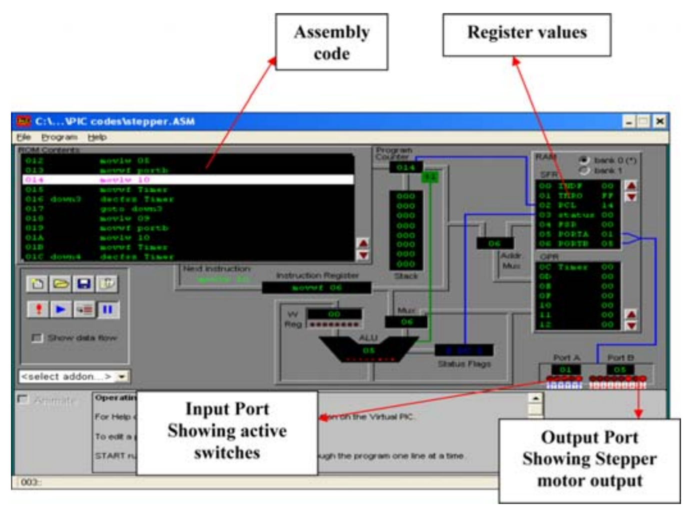

Fig. 9. Simulation program for the mechatronics kit.

C. CNC Machine

This project concerned the design, implementation and control of a computerized numerical control (CNC) machine tool. The designed CNC machine is a fully integrated system, comprising motors, frames, cutters, drive circuits, microcontroller and computer interface, combined with CAD/CAM software, that enhances the automated manufacturing process.

The CNC specifications were: three axes for movement, usage for drilling and milling, variable drilling speed, machine size set to 1.5 m $\times$ 1 m $\times$ 1.2 m, capability to work with linear and circular shapes, work pieces to be used are plastic and aluminum, work piece maximum dimension is 20 cm $\times$ 20 cm $\times$ 20 cm, three modes of operation: manual, automatic, and computer control, and software should be user-friendly.

The design team began by contemplating the choice of motors. It was decided that the XYZ axis movement would

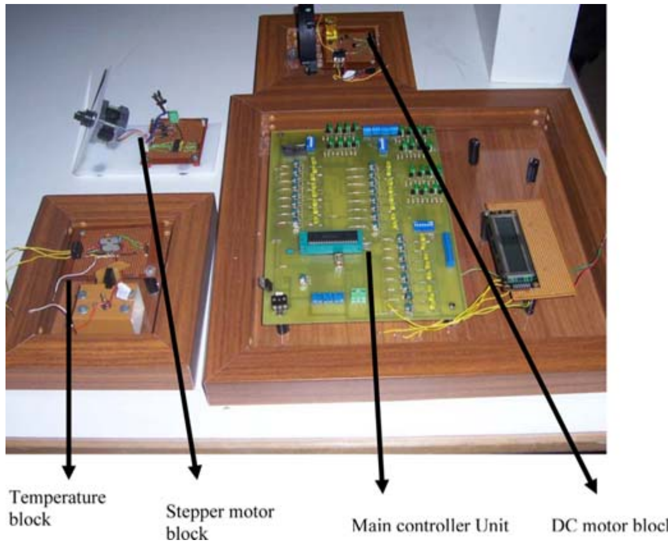

Fig. 10. Mechatronics kit.

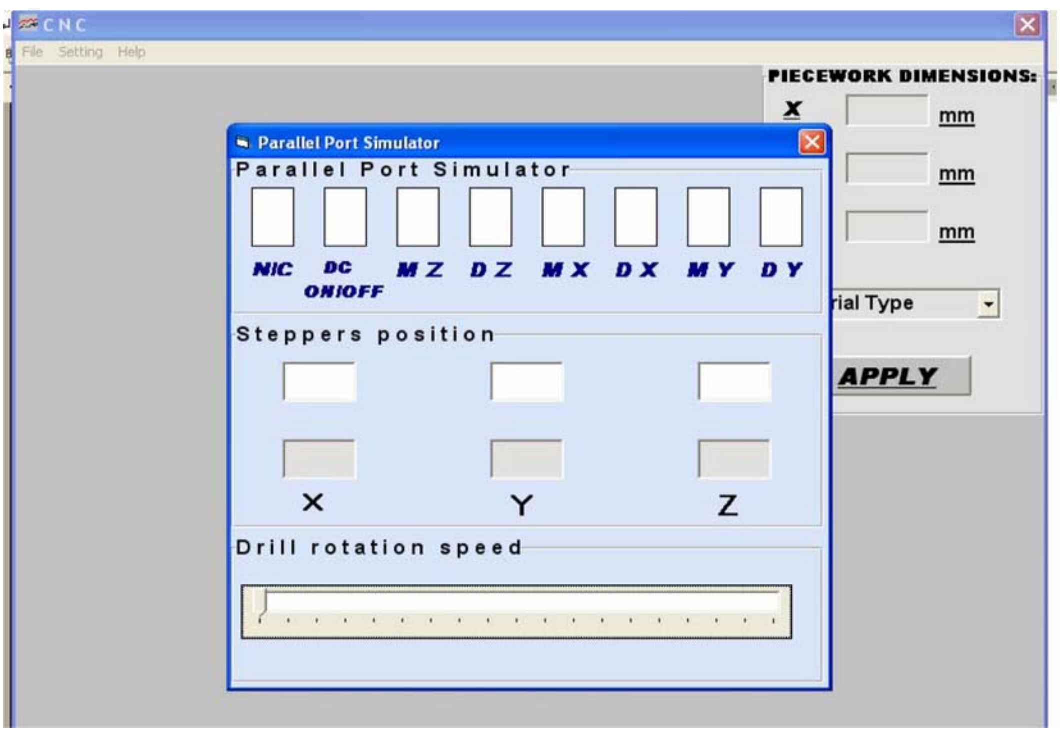

Fig. 11. CNC user interface.

be driven by three stepper motors, mainly due to the simplicity of their interface and control. Stepper motors were used (over servo dc) for positioning, in order to avoid the use of positioning sensors, and to produce the highest torque at low speeds. The total torque needed to move the axis in the x and y directions were calculated, and motor performance curves were used to select the appropriate motor specifications. An ac motor was to be used for drilling because of its high torque. The speed specifications were set to be between 50 to 1500 RPM. A shaft encoder was placed on the motor for position measurement.

Visual basic was chosen as the interface software for its user-friendly screen, and its compatibility with Windows-based operating systems. The software features also included a tasks-sorting program to minimize operation time and to provide the ability to save drawings. The user interface screen is shown in Fig. 11.

Computer communication with the microcontrollers was set through the parallel port. MOSFET power transistors were used to activate the stepper motors (4 transistors for each motor). The PCBs are shown in Fig. 12.

All the design and implementation, including the mechanical frame, circuits, and software was carried out by the students at PU. The only parts purchased were the four motors, the work area frame, the computer, and the IC components. Fig. 13 shows the final functioning CNC machine.

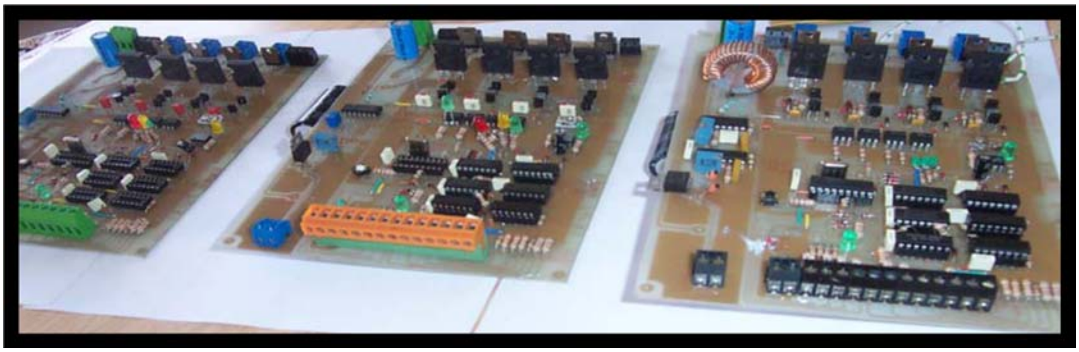

Fig. 12. Controller PCBs used in the CNC design.

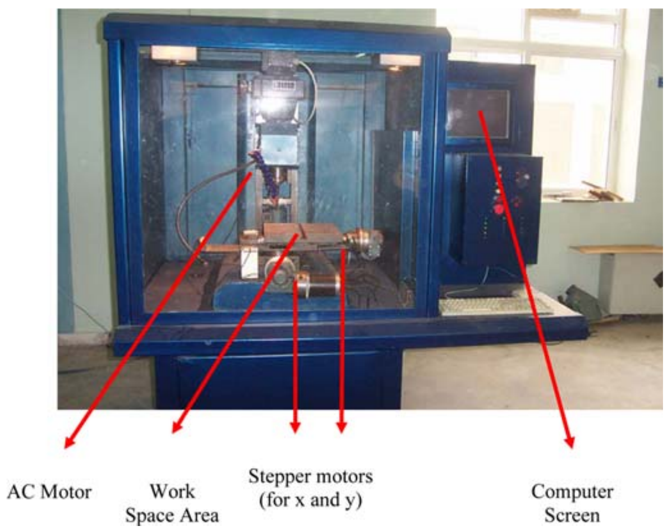

Fig. 13. CNC built machine.

VI. Conclusion

The success of a mechatronics engineering program is directly related to the practical implementation of fully integrated physical systems. Such programs should focus on mechatronics design concepts and their implementation. Students should be able to realize their design objective and produce a working prototype. One way to reach this goal is to conduct a well-organized seminar for students working on their senior project that promotes the thought process, necessary for good design and practical implementation. In this paper, the seminar material and structure was explained in detail, the student project design methodology was given, and three successful projects were presented as examples. Furthermore, an evaluation of the seminars was provided which showed a remarkable improvement in students' projects.

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