An alternative approach in mechatronics curricular development at AFEKA – Tel-Aviv Academic College of Engineering and at Tel-Aviv University

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Abstract The AFEKA – Tel Aviv Academic College of Engineering has developed a program in mechatronics studies designed not just for students of mechanical engineering but for every student in any field of engineering, as well as for experimentalists in natural sciences. This program supplies the students with tools that allow them to gain interdisciplinary insights and to carry out interdisciplinary final projects. In this paper we outline this program and give a detailed description of some unique features of the mechatronics laboratory.

Keywords mechatronics; laboratory; interdisciplinary

Introduction

In an interdisciplinary world, the term ‘mechatronics’ is no longer a futuristic term but rather a contemporary one (as with bioengineering, robotics or nanotechnology). As such, many engineering departments have developed impressive curricula in mechatronics as part of their programs in mechanical engineering [1–3]. Some departments even offer a BSc degree in mechatronics [1]. At AFEKA – Tel-Aviv Academic College of Engineering, we feel that if mechatronics is to be a truly interdisciplinary field of study, then it should not be restricted to students of mechanical engineering, but be offered to every student in each of the three departments of our school: mechanical engineering (ME), electrical engineering (EE) and software engineering (SE). Since the academic year 2000–01, we have been offering two courses in mechatronics *designed for all three departments*. Both courses are obligatory for each ME student. For students in either of the other departments, both are elective. Students who attend these courses acquire experience in carrying out interdisciplinary projects, which they value. Consequently, there is a growing number of final projects for the BSc degree which are interdisciplinary.

In this paper, we describe the key features of our mechatronics courses that make them relevant to many disciplines in engineering, as well as for students in chemistry and physics; these courses have been taught in parallel at the School of Chemistry in Tel-Aviv University (TAU).

Structure of mechatronics studies and course organization

The general purpose of the mechatronics courses is to expose students to an interdisciplinary field, one which is a principal industrial field. The more specific goal is to provide the students with tools to perform a mechatronics-oriented final project that counts towards the BSc degree and that will equip them with skills that will appeal to a potential employer.

In the light of this, we offer two courses of mechatronics. One is a weekly, one-semester, four-hour laboratory course. It provides students with both a theoretical background and applied tools with which they can solve problems in the field of mechatronics. This course is divided into four parts:

(1) The students first study the C programming language, along with data representation in binary systems, bit manipulation, basic computer architecture, and absolute memory and I/O port accessing.
(2) Then, the students learn the programming graphical user interface (GUI). We used the National Instrument [4] Lab Windows/CVI environment to write the program and the GUI. This environment was chosen because it has several distinct advantages: complete transparency to the programmer who programs in C, as there is no need to write any source code line to produce this GUI; full compatibility with ANSI C, and compatibility with C++ using an external compiler like visual C; a wide range of support in addressing many hardware devices and instruments; low-level support drivers for I/O port addressing; and a wide range of libraries (advance analysis, PID, TCP, Internet, GPIB, VISA, RS-232, VXI, etc.).
(3) Next, advanced toolbox libraries are introduced. We emphasize the use of advanced numerical analyses, data acquisition, signal processing, control, and communications. During the semester, the students numerically work out basic issues which are engaged with mechatronics – heat transfer, vibration, fluid flow, statics and dynamics.
(4) Lastly, as a final assignment of this course, the students read and write analog and digital signals from an oscilloscope and a function generator, through standard ports such as RS-232 and GPIB.

The other mechatronics course is a weekly, one-semester, five-hour laboratory course. It provides the students with practical mechatronics. We begin with basic hardware elements, such as counter timers, power-switching devices, power-amplifying devices (used in electromechanical control systems) and PWM controllers. All these devices are combined into a tailor-made I/O board, designed for this course (see below). The students experience multi-threading programming, real-time applications, and the use of the Transmission Control Protocol (TCP) for control and data acquisition. Then, the students are fully prepared to control DC motors, stepper motors, heating elements, thermoelectric coolers, and sensing elements, such as photo-resistor thermistors, opto-couplers and photodiodes. The final assignment of this course is chosen by the students themselves. They carry out an experiment in which they use the program they developed to PID control a system of their choice. In this experiment the students characterize the typical parameters of the system and present its real-time response.

Detailed description of the hardware

In this section we provide a detailed description of the IO drive 2000 interface board, the embedded evaluation board, and the systems that are controlled by the students. Students routinely use the IO drive 2000 interface board coupled to the PC to perform all the tasks on these courses. Students who wish to acquire further experience for their final project are given the embedded evaluation board to use for practice in their free time.

IO drive 2000 interface board

This board, presented in Fig. 1, was tailor-made for the mechatronics courses; however, it can also be used for other laboratory courses. It is unique because it contains the required power devices on board and is externally connected to the computer (to laptop computers as well as desktop computers). This allows for portability of the entire experimental set-up and enables trouble-free computer upgrading.

The board connects to the parallel port, communicates with the computer using the Extensible Provisioning Protocol (EPP), and enables a data transfer rate of one megabyte per second (depending on the operation mode and the specifications of the computer). The board requires an external power supply with a flexible voltage range (12–36 V) and current that meets the requirements of the system.

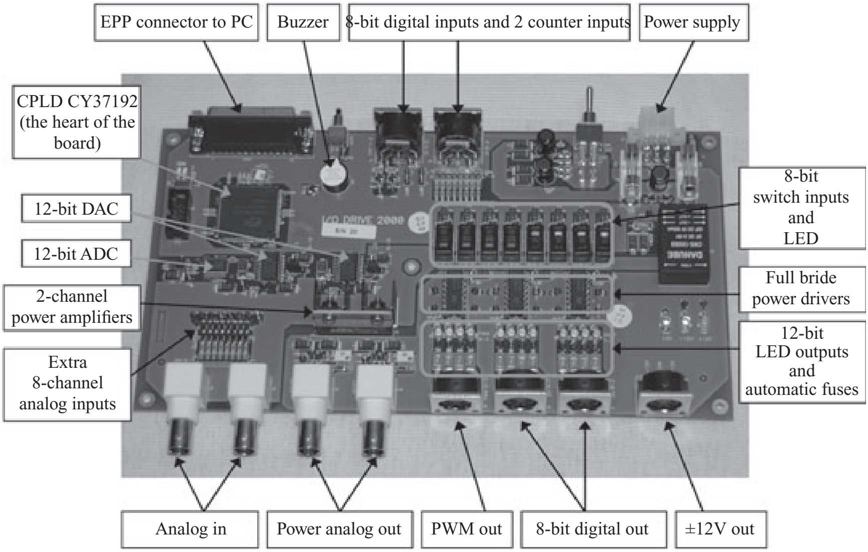


Fig. 1 *The IO drive 2000 interface board.*

This board has an 8-bit digital input that reads active and passive digital signals within the range of [0 V, 5–50 V]. This allows TTL levels to be read, as well as other standard levels of industrial and scientific equipment. The data reading rate can reach up to 1 MHz.

This board has an 8-bit digital output that enables it to simultaneously drive devices that consume up to 1 A each. In addition to the 8-bit digital output, there is a four-channel programmable PWM output that also enables the simultaneous operation of devices that consume up to 1 A each. The PWM switching frequency is 100 kHz, while the duty cycle can reach 256 levels, which represent 0.4–100%. All output channels permit inward and outward current flow, while the data change rate in the outputs can reach up to 1 MHz.

The board contains two independent analog outputs. Each supplies a variable voltage within the range of ±10 V, with a resolution of 12 bits, and a current of up to 1 A. The data change rate in the output can reach 100 kHz.

There are also eight independent analog inputs. Each enables a variable voltage to be read, within the range of ±10 V, with resolution of 12 bits. The data reading rate can reach 100 kHz.

The board also includes two programmable counter timers of a specific architecture, which can be modified by altering the programmable logic. The outputs of the counter timers are connected outwards and enable a current flow of up to 20 mA. The board can send an interrupt request to the computer through the parallel port. The interrupt can be triggered by the counter timer or by the user.

Embedded evaluation board

In addition to the IO drive 2000 interface board, we designed an alternative stand-alone embedded board that allows the user to control the systems without using a PC, as shown in Fig. 2. This prepares the student to work in any environment that requires portability or compactness of design.

This board is based on a Microchip [5] PIC16F877 8-bit microcontroller. This controller includes 8 kbyte of flash memory for programs, 256 byte of RAM for data storage and 128 byte of EEPROM. It contains five bi-directional ports and peripheral devices (among which are three timers), five analog input channels, a synchronous UART, an asynchronous UART, an I^2C communication bus and an interrupt controller.

The board itself contains additional peripheral devices, such as a matrix keyboard, eight digital switches, a 16-bit bi-directional bus, an 8-bit digital output with an eight-LED indicator, an LCD alphanumeric display, two analog output channels and a buzzer.

The development procedure, namely, programming, compiling, linking and debugging, is performed in an MPLAB environment, which is freely distributed by Microchip [5].

Laboratory equipment for processes control

The IO drive 2000 interface board is equipped to control various systems, for example to govern light intensity, temperature, speed of a DC motor, or the angle

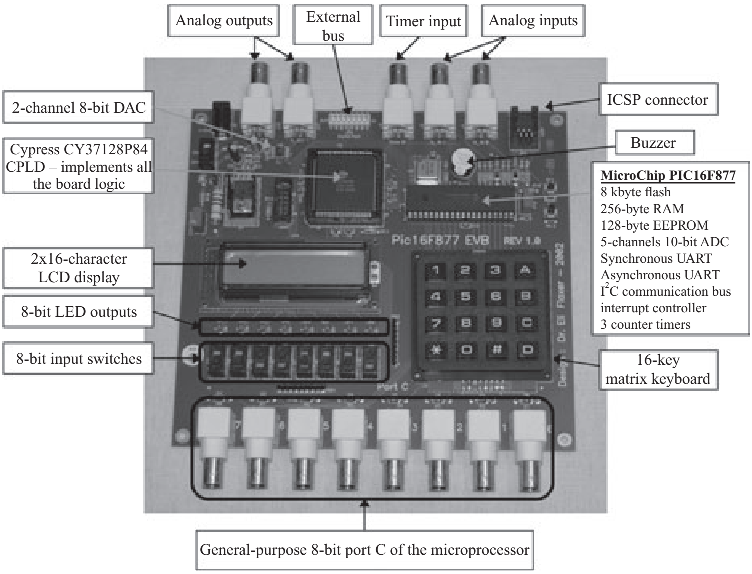


Fig. 2 *The PIC EVB evaluation board for the Microchip PIC 16/18 microcontroller.*

controlled by a stepper motor. Fig. 3 shows a typical workstation at the laboratory, with the IO drive 2000 interface board and a compact box containing the experimental set-up for the control of light intensity. This unit can be replaced by others for different control purposes.

Prior to describing the various systems to be controlled, we must indicate that the chosen control units are not necessarily linear over all the measurement range, as in real life. This is undesirable but can be easily compensated for, as we control the systems by computer and so the software can produce a corrected transfer function (by interpolation, hash function or table of values).

Light intensity control

The radiant element is a 12 V/1 A light bulb with a time constant of 30 ms. The sensing element is a photo-resistor that changes its resistance in a range from 100 Ω (for full daylight) to 1 MΩ (darkness). This photo-resistor is serially connected to a 10 kΩ resistor, and the two form a voltage divider that depends on the light bulb's intensity. The output of this voltage divider runs between 0 V and 10 V. Since the radiant element is a light bulb with a finite heat capacity, it has a typical time constant (30 ms, in our system), which can be measured using the sensing element. The time constant of the photo-resistor is in the range of a few microseconds, and therefore negligible with respect to the time constant of the light bulb. The set-up of this experiment is presented in Fig. 4(a).

Fig. 3 *A typical laboratory station, designed for the use by one or two students simultaneously. The computer is an all-in-one IBM PC, which saves laboratory space and allows the latter to contain additional stations. Note at the middle left side of the picture the compact external IO 2000 drive, which contains the required power devices and below it, the compact box that contains the experiment set-up for light intensity control.*

Temperature control

A 5 × 5 × 1 mm piece of copper with a heat capacity of ~0.1 J/Cº is attached to the hot side of a thermo-electric cooler (TEC), while its cold side is attached to a heat-sink. The temperature of this copper piece is sampled by a negative temperature coefficient (NTC) thermistor. The room temperature resistance of the sampling thermistor is 10 kΩ, while its B-constant is 3380 K, which leads to a resistance of 70 kΩ at –40ºC and 3 kΩ at 60ºC. The thermistor is serially connected to a 10 kΩ resistor and both form a voltage divider whose configuration depends on the temperature of the copper. The output of this divider runs between 1 V and 8 V. The heat transduction element is a TEC. This TEC has a power of 18 W, maximum current of 2.1 A, maximum voltage of 16 V, resistance of 6.3 Ω, and a maximal temperature difference (ΔT) of 70ºC. These parameters are compatible with the specifications of the IO drive 2000 interface.

The use of a TEC as the heat transducing element has a significant advantage over other methods of temperature control. Conventional heating elements can only introduce heat into the controlled element and therefore the cooling of the controlled element is dictated by the surroundings. The usage of a TEC allows the user either

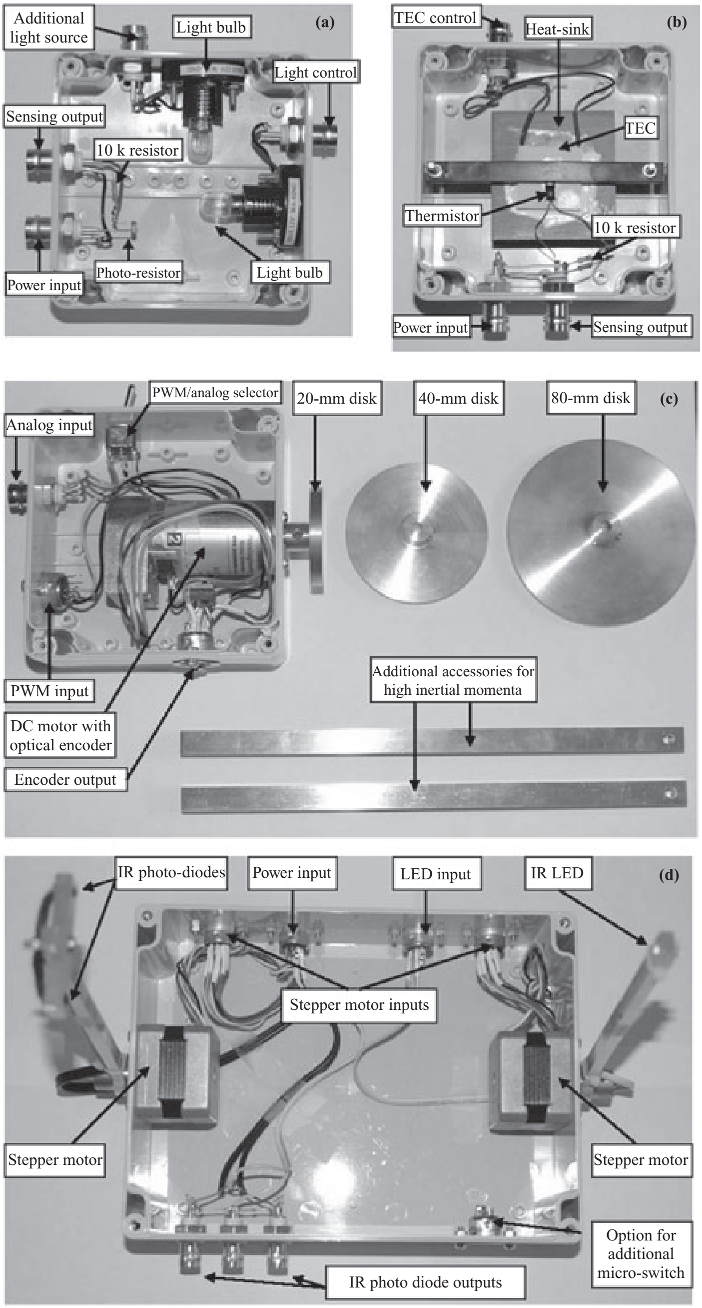


Fig. 4 *The experimental set-up used at our mechatronics laboratory for (a) light intensity control, (b) temperature control, (c) DC motor control, and (d) stepper motor control. (A detailed description of each set-up is given in the text.)*

to inject or to absorb heat from the controlled element, and this allows for faster and more efficient temperature control. Although TECs are usually expensive, we have chosen a relatively low-cost one, due to a restricted budget. The set-up of this experiment is presented in Fig. 4(b).

Stepper motor control

This experimental set-up is designed to demonstrate the principle of homing in on an object by the angular tracking of a light beam. A more elaborate version of this principle is used to focus the reading head of optical-medium drives and to fine-tune the cantilever of atomic force microscopes.

The position of a light source is monitored by a pair of adjoining photo-sensors. The light source is directed to strike the photo-sensors precisely in the middle, where the intensities of light sensed by the photo-sensors are equal. A deviation in position causes more light to strike one of the sensors than the other, and thus creates a measurable difference in light intensities. The difference in intensities is the feedback that informs the servo control that the position of the light source needs to be corrected, and the ensuing correction is performed automatically.

An infrared light emitting diode (LED) is the illuminating element, while the photo-sensing elements are infrared photo diodes (PDs). Each of the elements, LED and PDs, is mounted on a rotating arm 15 cm in length, which is coupled to a bipolar stepper motor of 200 steps per revolution. Each of the stepper motors independently (manually or under computer control) changes its orientation to center the light emitted by the LED exactly in the middle of the PDs, as described in the previous paragraph. Thus, the LED itself is positioned. The maximal angular velocity of each motor (including the load) is about 3°/ms. The set-up of this experiment is presented in Fig. 4(d).

DC motor and encoder

In an analogous experiment to the one with the stepper motor, we could have chosen to control the angle or the speed of a DC motor. In order to teach the students a wider variety of subjects, we chose to control the speed of the motor rather than its angle again. Three brass disks, each a width of 5 mm, diameters of 40, 60, and 80 mm, and moments of inertia of $11 \cdot 10^{-6}$ kg·m^2, $57 \cdot 10^{-6}$ kg·m^2, and $180 \cdot 10^{-6}$ kg·m^2, respectively, are attached to the shaft of a DC motor and accelerated by the motor. The purpose of this experiment is to maintain the speed of the motor at a predetermined constant value under different loads. If disks of different loads are attached to the shaft of the motor, a different torque and a different time are required to achieve the predetermined value, and so a different power must be supplied for each load. The motor used is a 24 V DC motor that has a torque of $11 \cdot 10^{-3}$ N·m, a no-load speed of 7800 rpm, a resistance of 12 Ω, and an inductance of 6 mH.

The speed of the motor is sensed by an incremental optical encoder, which is integrated into the motor. The encoder produces 500 pulses per round. The number of pulses over a time interval, ΔT, is sampled by the counter timer of the IO drive 2000. Thus, the speed of the motor can easily be calculated. The experiment set-up is presented in Fig. 4(c).

One may observe that in this experiment one can use the analog output of the IO drive 2000 or, alternatively, the PWM output, to drive the motor. The experiment can therefore help students to understand the difference between these two modes of operation.

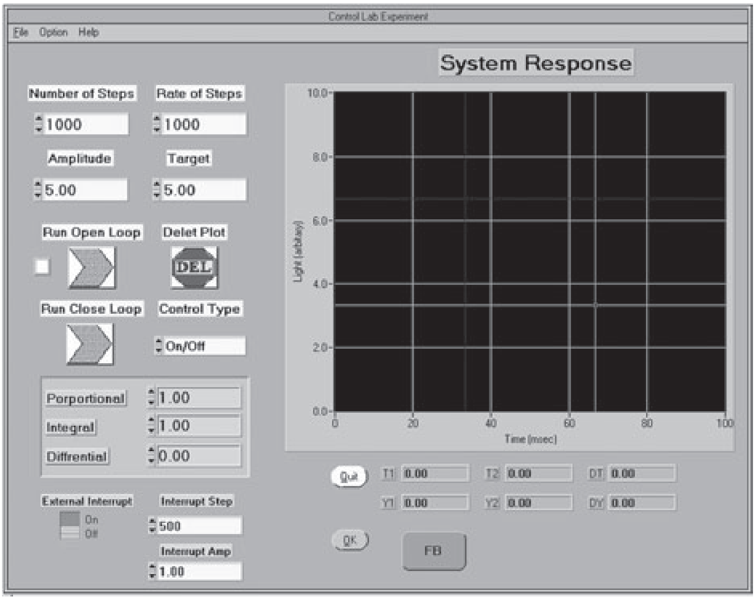
Notable characteristics of the software

As mentioned earlier, we use the CVI programming environment to build the GUI (presented in Fig. 5) and control the above experiments. However, there is no objection to using the LabView [4] programming environment for the same purposes, as the drivers and libraries of the two programming environments are fully compatible.

Two elements of the software are worth mentioning:

(1) The option of multi-threading programming allows the user to run several parallel processes. For mechatronics this capability is essential, since real-time applications are dealt with. A typical example is the operation of the angle control experiment described above, where two motors simultaneously operate to center the light source between the sensing PDs.

(2) The option of using TCP communication allows the user to *remotely control* and *sense* the experiment.



Number of Steps 1000
Rate of Steps 1000
Amplitude 5.00
Target 5.00
Control Type On/Off
Porportional 1.00
Integral 1.00
Diffrential 0.00
Interrupt Step 500
Interrupt Amp 1.00
T1 0.00
T2 0.00
DT 0.00
Y1 0.00
Y2 0.00
DY 0.00

Fig. 5 *A typical GUI screen designed by a student for PID control of any of the experiments.*

Cost analysis

The laboratory that we use for these courses is also used for other typical electronics courses. Therefore, some of the equipment mentioned in this article was not purchased specially for the mechatronics laboratory. Table 1 lists all the equipment required for these laboratories, specifying what existed and what needed to be purchased for the mechatronics laboratory courses. Note, that the costs of production of the tailor-made data-acquisition board and the tailor-made embedded board have also been included. As indicated above, we use a National Instrument CVI environment. In such a programming environment a multi-meter, an oscilloscope, and a function generator can be implemented in software. However, this high-quality equipment already existed in the laboratory, so there was no need to do so.

Participation in mechatronics studies

We have examined the number of students who have participated in the mechatronics courses over the years. In Fig. 6 we present the total numbers, at both AFEKA and TAU; The number of participants is constantly rising.

At AFEKA, where the courses are obligatory, we had to organize second and third study groups, as the laboratory is limited to 20 participants at a time. At TAU, where these courses are elective and are taught only once a week, a waiting list formed. Some of the students had no choice but to register for the next academic year. It is also apparent that the distribution of students among the different departments at AFEKA and the different degrees at TAU broadened: while in 2002 all the participants at AFEKA were ME students, by 2005 the number of students of EE and SE had increased. At TAU, due to student demand (and needs), the courses are no longer restricted to undergraduate students, but offered to graduate students as well.

It is important to mention that at AFEKA all the elective courses of a certain department are part of specialization programs in that specific department, except for the mechatronics courses, which are inter-departmental. Students usually prefer to attend a course which is part of their specialization program rather than an inter-departmental course. Therefore, any comparison of the extent of participation of students of EE or SE in mechatronics courses and in other elective courses is

TABLE 1 *Cost analysis of equipment (per station)*

Hardware	Approximate cost ($)
Desktop/laptop computer – IBM/HP	1500
External power data-acquisition board – IO drive 2000 (dedicated)	1350
Embedded board – PIC Evb (dedicated)	350
Controlled components set-ups and accessories (dedicated)	700–1800
100 MHz digital oscilloscope – Tektronix TDS 220 or compatible	In laboratory
Function generator – Agilent 33120A or compatible	In laboratory
Multi-meter –Tektronix TX3 or compatible	In laboratory
Triple-output power supply – OEM	In laboratory

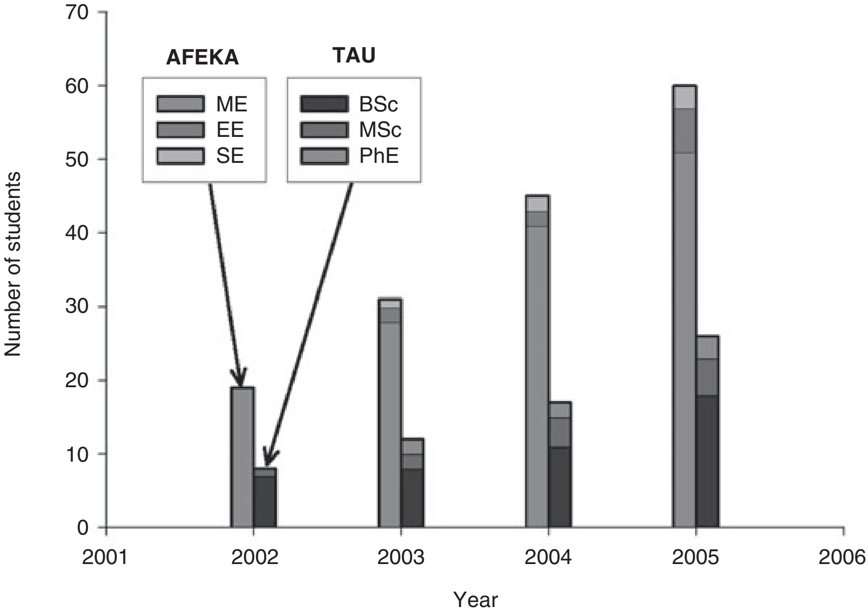


Fig. 6 *Numbers of students who attended the mechatronics courses at AFEKA and at TAU. Each bar is divided into three sections that represent the distribution of participants among the different departments at AFEKA or different degrees at TAU.*

irrelevant. Despite this fact, one can note a gradual rise in the number of EE and SE students on the mechatronics courses (see Fig. 6).

At the end of each course, the participating students are asked to respond to satisfaction surveys. The surveys contain several statements regarding the quality of the course and the lecturer. The student have to grade these from 1 to 7 (1 = I do not agree with the given statement, 7 = I strongly agree with the given statement). Some typical statements are:

- I am satisfied with the course.
- I am satisfied with the lecturer.
- The course is well organized.
- The lectures are clear.
- The lectures are intellectually challenging.
- The lectures are interesting.

These statements are usually highly graded. However, the most interesting part of the survey is the general comment part, where the students are encouraged to comment on every possible aspect of the courses. Some interesting responses were 'to establish some advanced courses in which we can control real scientific apparatus', 'to learn how to design such interface boards' and 'mechatronics is a leading field of technology which is essential to finding a job. It enables us to find our first job with no difficulties, in contrast to others who did not attend the mechatronics courses'.

The participation statistics, as well as student satisfaction reviews, are an indication of the current need for such courses and call for additional advanced courses in mechatronics.

Final project of the BSc degree at AFEKA

The importance of mechatronics, as a growing interdisciplinary field, has led us to offer students the opportunity to submit interdisciplinary projects as their final projects for their BSc degree. Typical projects include a macroscopic model of a scanning probe microscope (SPM) and a fruit/vegetable firmness tester:

(1) An SPM uses fine piezoelectric transducers controlled by feedback mechanisms to scan, with a very sharp tip at minute distances, the surfaces of samples, and thus to map those samples. The interaction between the tip and the sample is converted into an electrical signal that is sampled and processed by a computer. In our macroscopic model, the piezoelectric transducers are replaced by three stepper motors while the tip is replaced by an optical fiber. The sample is illuminated by light that emerges from the optical fiber and the interaction between the tip and the sample is represented by the scattering of the light, which is monitored by the optical fiber.

(2) The fruit/vegetable firmness tester uses an accelerometer, covered by a flexible tube, to hit a fruit or vegetable at a fixed speed. With the impact, the accelerometer produces an electrical signal that contains information about the ripeness of the fruit. The electrical signal is then filtered, amplified and processed by a microprocessor.

As these projects are still ongoing, we present their mechanical design in SolidWorks format [6] in Fig. 7.

The number of students who carry out such interdisciplinary projects is well correlated with the number of students who attend the mechatronics courses, as discussed in the previous section.

Scientific projects at TAU

Some of AFEKA's students who pursue their studies towards higher degrees in engineering, and some experimentalists at the Department of Chemical Physics at TAU, perform projects in mechatronics as an inherent part of designing the experimental apparatus on which they perform their research. In Figs 8, 9 and 10, we present three typical scientific projects that are the direct outcome of our courses:

(1) *A linear piezoelectric stepper motor, which is designed to translate an object in sub-micron steps, forwards and backwards*. In this project, the object to be translated is the tip of an SPM. One important element of the SPM that exten-

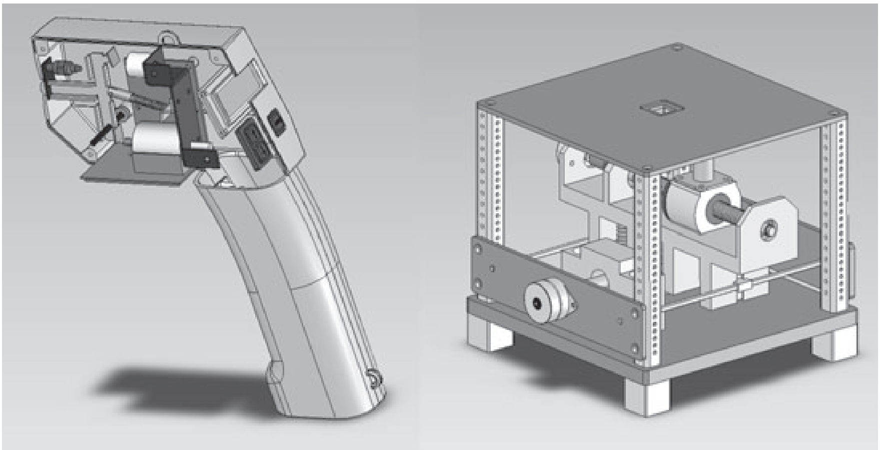


Fig. 7 *SolidWorks*^{TM} *designs of ongoing final projects. Right: A macroscopic model of an SPM. Left: A fruit/vegetable firmness tester. The two designs are not to the same scale. (A detailed description of these designs is given in the text.)*

sively affects its design and performance is the coarse approach mechanism [7]. This mechanism is used to bring the tip from a set-up position, 'far away' from the sample (several mm), to a scanning position, 'very close' to the sample (<1 μm), by fast sub-micron steps. Fig. 8 presents the experimental set-up designed to characterize the linear stepper motor, prior to assembling it into the SPM [8].

(2) *A linear mirror displacement mechanism driven by a stepper motor, which is part of an optical set-up in a pump–probe experiment*. In this experiment, the kinetics of proton transfer in condensed-phase molecular systems are monitored by using timed femto-second lasers [9]. The spatial resolution of the mirror, which sets the time delay between the 'pump' beam and the 'probe' beam, is 0.1 μm, which is equivalent to a temporal resolution of 0.3 fs. Fig. 9 shows the experimental set-up.

(3) *A multi-channel high-voltage programmable waveform generator for manipulating piezoelectric transducers*. This project is aimed at producing a three-dimensional inertial drive slider in cryogenic SPM systems. Inertial sliders [10, 11] produce a series of discrete steps, each of which uses a full expansion of a piezo drive and relies on the 'tablecloth trick' of slip–stick motion. A translation stage riding on a smooth support can be accelerated using a piezo actuator. Due to friction, the stage will accelerate up to a certain limit. If the motion is suddenly reversed (by reversing the piezo voltage as quickly as possible), the translation stage will not follow the reversed movement. Fig. 10 shows this experimental set-up [12].

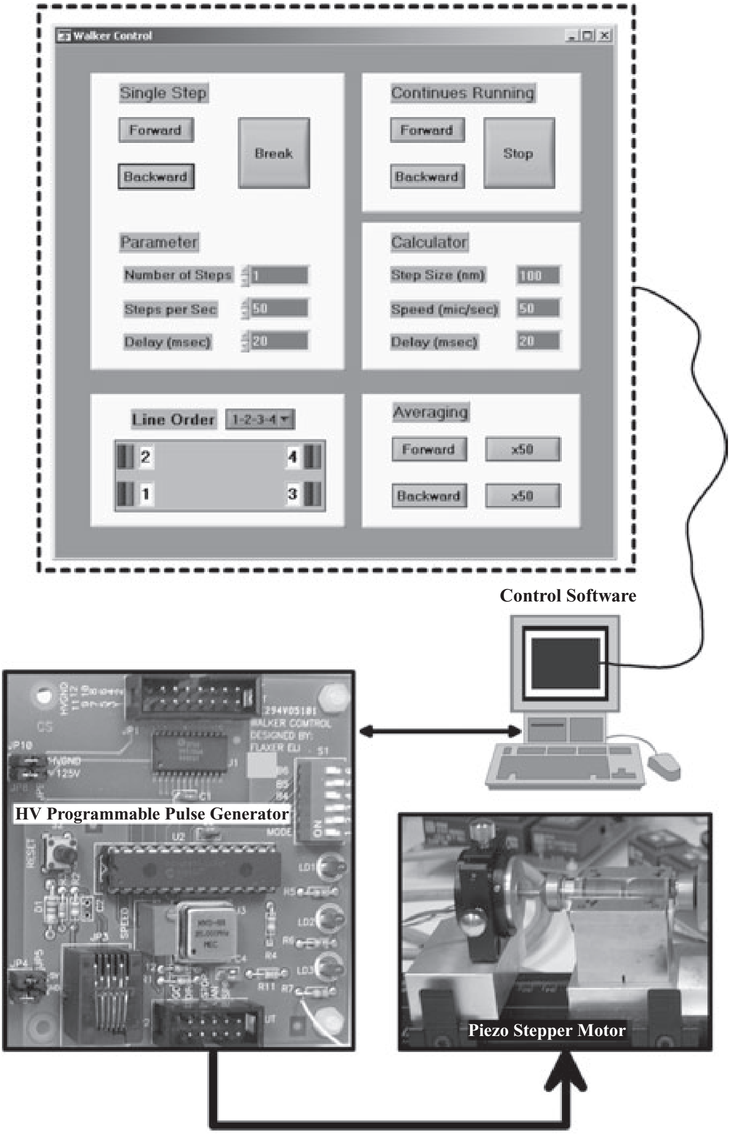


Fig. 8 *The experimental set-up for the characterization the linear stepper motor, prior to assembling it into an SPM. (A detailed description is given in the text.)*

Conclusions and future work

The mechatronics laboratories were initially offered at the college only to students majoring ME, and at the university only to BSc students who intended to specialize in experimental chemical physics (at the School of Chemistry). However, as these

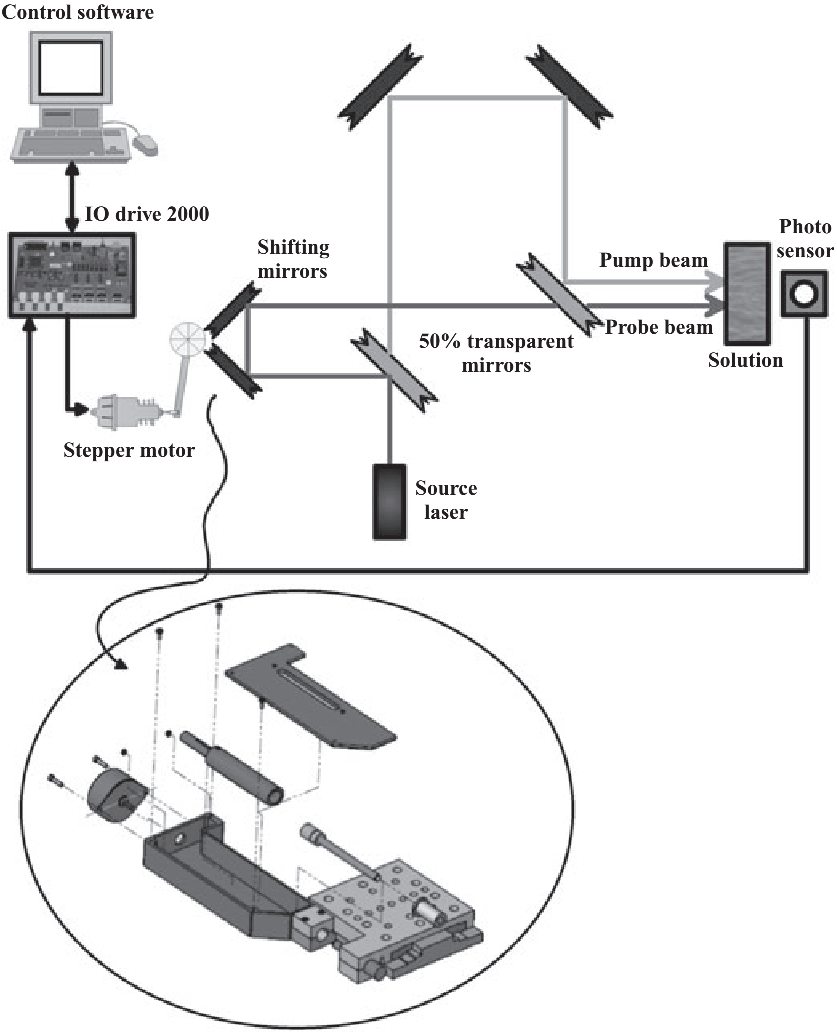


Fig. 9 *A schematic of the optical experimental set-up of the pump–probe experiment and a detailed design of the high-resolution screw that sets the position of the shifting mirrors. (A detailed description is given in the text.)*

laboratories, at both the university and the college, attracted great attention, the increased enrollment soon made us open them to every student and, accordingly, modify them to answer the needs of students who came from different academic disciplines.

Mechatronics is currently not a research focus at AFEKA; however, in the near future AFEKA intends to establish an advanced program of interdisciplinary studies

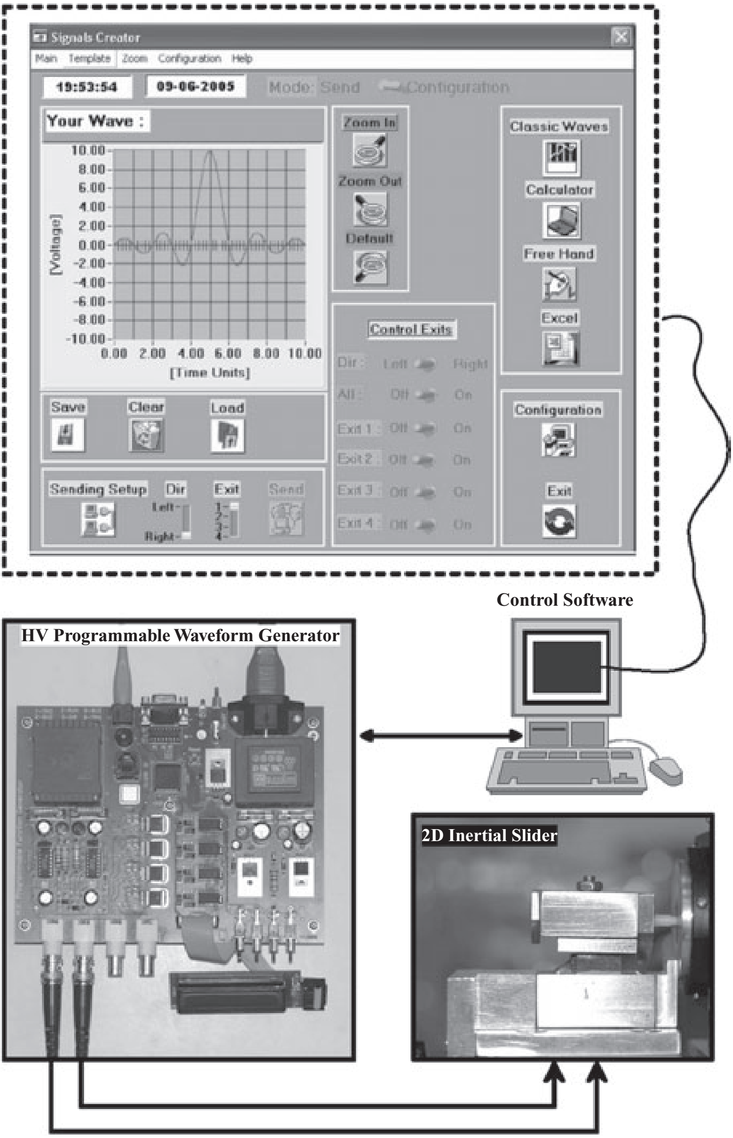


Fig. 10 *The experimental set-up of the multi-channel high-voltage programmable waveform generator that manipulates the piezoelectric transducers of an inertial drive slider in an SPM. (A detailed description is given in the text.)*

in engineering, where mechatronics will become a research focus and mechatronics studies will occupy a considerable part of the curriculum of this program.

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