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 which was \textit{inclusively} 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 provide the outline of this program together with a detailed description of some unique features of the mechatronics laboratory.

\textbf{Keywords:} Mechatronics; Laboratory; Interdisciplinary;

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1. Introduction

In an interdisciplinary world the term mechatronics (similar to bioengineering, robotics or nanotechnology) is no longer a futuristic, but rather, a contemporary term. As such, many engineering departments have developed impressive curricula in mechatronics as part of their programs in mechanical engineering\textsuperscript{1,2,3}. Some departments even offer a B.Sc. degree in mechatronics\textsuperscript{1}. We, at AFEKA – Tel-Aviv Academic College of Engineering, 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 of each of the three departments of our school: mechanical engineering (ME), electrical engineering (EE) and software engineering (SE). Since the academic year 2000-2001, we have been offering two courses in mechatronics designed for all three departments. Both courses are obligatory for each ME student. For students of either of the other departments, both are elective. Students who attended these courses acquire experience in carrying out interdisciplinary projects. Consequently, there is a growing number of final projects for the B.Sc. Degree which are interdisciplinary because these students find it valuable to deepen their experience with such projects.

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; as these courses have been taught in parallel in the Tel-Aviv University (TAU) at the School of Chemistry.

2. Structure of Mechatronics Studies and Course Organization

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

In the light of this, we offer two courses of mechatronics. The first is a weekly, one semester, 4-hour laboratory course. It provides the 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 4 parts:
The students first study the C programming language while deepening the subject of data representation in binary systems, bit manipulation, basic computer architecture, and absolute memory and I/O port accessing.

Then, the students learn the programming graphical user interface (GUI). We used the National Instrument Lab Windows/CVI environment to write the program and the GUI. This environment was chosen because it has several distinct advantages: 1) A complete transparency to the programmer who programs in C, as there is no need to write any source code line to produce this GUI. 2) Full compatibility with ANSI C, and compatibility to C++ using an external compiler like visual C. 3) A wide support range in addressing many hardware devices and instruments. 4) Low-level support drivers for I/O port addressing. 5) A wide range of libraries (Advance analysis, PID, TCP, Internet, GPIB, VISA, RS-232, VXI etc.).

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.

Finally, 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 as RS-232 and GPIB.

The second course is a weekly, one semester, 5-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. The students experience multi-threading programming, real-time applications, and uses TCP protocol 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 second 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.

3. Detailed Description of the Hardware

In this section we provide a detailed description the IO drive 2000 interface board, the embedded evaluation board, and the systems that are controlled by the students.

3.1 IO drive 2000 interface board

This board, presented in Figure 1, was tailor-made for the mechatronics courses, however, due to some of its features, it can 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. Therefore, it can be connected to both laptop computers and to all-in-one computers. Thus, it allows for portability of the entire experimental setup and enables trouble-free computer upgrading.

The board connects to the parallel port, communicates with the computer using the EPP protocol 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 range (12-36 Volts) and current that meets the requirements of the system.

This board has an 8-bit digital input that reads active and passive digital signals within the range of [0V, 5-50V]. This range allows to read TTL levels, 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 4-channel programmable PWM output that also enables 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 that 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 Volts, with a resolution of 12 bit, and a current of up to 1 A. The data change rate in the output can reach 100 KHz.

There are also 8 independent analog inputs. Each enables to read a variable voltage within the range of ±10 Volts, with resolution of 12 bits. The data-reading rate can reach 100 KHz.

The board also includes 2 programmable counter timers of a specific architecture, which can be modified by altering the programmable logic. The counter timer outputs 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.

### 3.2 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 Figure 2. This prepares the student to work in any environment, which requires portability or compact ability.

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

The board itself contains additional peripheral devices such a matrix keyboard, 8 digital switches, 16-bit bi-directional bus, an 8-bit digital output with an 8-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\textsuperscript{5}.

Students routinely use the IO drive 2000 interface board coupled to the PC to perform all the tasks of 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.
3.3 Laboratory Equipment for Processes control

The IO drive 2000 interface board is equipped to control various systems such as light intensity, temperature, speed of a DC motor, and angle controlled by a stepper motor. Figure 3 shows a picture of a typical working station at the laboratory, where one can note at the bottom left side the IO drive 2000 interface board and a compact box containing the experimental setup where light intensity is controlled. This unit can be replaced by others units for different control purposes.

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

3.3.1. Light intensity control

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

3.3.2. Temperature Control

A 5x5x1 mm piece of copper with a heat capacity of ~ 0.1 J/C° is attached to the hot side of a Thermo Electric Cooler (TEC) while its cold side is attached to the heat-sink. The temperature of this copper piece is sampled by Negative Temperature Coefficient (NTC) thermistor. The room temperature resistance of the sampling thermistor is 10kΩ while its B-Constant is 3380K which leads to a resistance of 70kΩ at -40°C and 3kΩ at 60°C. The thermistor is serially connected to a 10kΩ resistor and both form a voltage divider whose configuration depends on the temperature of the copper. The output of this divider runs
between 1V-8V. The heat transduction element is a TEC. This TEC has a power of 18 Watt, maximum current of 2.1 A, maximum voltage of 16 V, resistance of 6.3 $\Omega$, and a maximal temperature differences ($\Delta T$) of 70°C. These parameters are compatible with the IO drive 2000 interface specifications. The use of a TEC as the heat transducing element has a significant advantage over other methods of temperature control. In conventional modes, the heating element 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 both to inject or to absorb heat from the controlled element and thus allows for a faster and more efficient temperature control. Although TECs are considered expensive elements, we have chosen a relatively low-cost one, due to a restricted budget. The setup of this experiment is presented in figure 4b.

3.3.3 Stepper Motor Control

This experimental setup is designed to demonstrate the principle of homing 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 the light to strike one of the sensors more than the other, and thus create a measurable difference in light intensities. The difference in intensities, which is no longer zero, is the feedback that informs the servo control that the position of the light source needs to be corrected and to do so automatically.

An infrared Light Emitting Diode (LED) is the illuminating element, while the photo-sensing elements are infrared Photo Diodes (PD). Each of the elements, LED and PDs, is mounted on a 15-cm-long rotating arm and coupled to a bipolar stepper motor of 200 steps per revolution. Each of the stepper motors independently (manually or computer-controlled) 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 ca. 3°/ms. The setup of this experiment is presented in Figure 4d.
3.3.4. DC Motor and Encoder

In an analogous experiment to the one with the stepper motor, one with a DC motor, we could have chosen to control the angle or the speed of the motor. In order to teach the students various subjects, we chose to control the speed of the motor rather than its angle. Three brass disks, each a width of 5 mm, diameters of 40, 60, and 80 mm, and moments of inertia of $11 \times 10^{-6}$ $\text{kg} \cdot \text{m}^2$, $57 \times 10^{-6}$ $\text{kg} \cdot \text{m}^2$, and $180 \times 10^{-6}$ $\text{kg} \cdot \text{m}^2$, 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 constant on a predetermined value under different loads. If one attaches disks of different loads to the shaft of the motor, a different torque and time is required to achieve the predetermined value. In order to achieve this predetermined speed, a different power must be supplied for each load. The motor used is a 24 V DC motor that has a torque of $11 \times 10^{-3}$ $\text{N} \cdot \text{m}$, a no-load speed of 7800 RPM, resistance of 12 $\Omega$, and 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 at a time interval $\Delta T$ is sampled by the counter timer of the IO drive 2000. Thus, the speed of the motor can easily be calculated. The experiment setup is presented in Figure 4c.

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. In this sense, this experiment is appropriate for the understanding of the difference between these two modes of operation.

4. Notable Characteristics of the Software

As mentioned earlier, we use the CVI programming environment to build the GUI (presented in Figure 5) and control the abovementioned experiments. However, there is no objection to use LabView programming environment for the same purposes as the drivers and libraries of both programming environments are fully compatible.

There are two elements in the software that are worth mentioning: 1) The option of multithreading programming which allows the user to run several parallel processes. For mechatronics this capability is very essential since one deals with real-time applications. A typical example is the operation of the angle control experiment, which was previously described, 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.

5. Cost Analysis

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

6. Participation in the Mechatronics Studies

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

At AFEKA, where the courses are obligatory, we had to open a second and a third studying groups, as the lab 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 this year. 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, in 2005 the number of students of EE and SE 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 irrelevant. Despite this fact, one can note a gradual rise in the number of participants of EE and SE in the mechatronics courses, as indicated before and shown in figure 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 statements 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 (excluding the responses regarding the quality of the lecturer) 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.

7. Final Project of the B.Sc. Degree at AFEKA

The importance of mechatronics, as a growing interdisciplinary field, has led us to offer the students to submit interdisciplinary projects as final projects for their B.Sc. degree. Typical representative projects which are underway are: a macroscopic model of a Scanning Probe Microscope (SPM) and a Fruit 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 these samples. The interaction between the tip and the sample is converted into an electrical signal that is sampled and processed by the computer. In our macroscopic model, the piezoelectric transducers are replaced by 3 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 that is monitored by the optical fiber.

2. A fruit/vegetable firmness tester uses an accelerometer covered by a flexible tube, to hit a fruit/vegetable, at a fixed speed. Due to 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 the format of SolidWorks in figure 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.

8. Scientific Projects at TAU

Some of AFEKA’s students that pursue their studies towards higher degrees in engineering, or experimentalists at the department of chemical physics at TAU, performed projects in mechatronics as an inherent part of designing the experimental apparatus on which they perform their research. In Figures 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
extensively affects its design and performance is the coarse approach mechanism\(^7\). This mechanism is used to bring the tip from a setup position, "far away" from the sample (several mm), to a scanning position, "very close" to the sample ($<1\mu m$), by fast sub-micron steps. Figure 8 presents the experimental setup 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 setup in a pump-probe experiment. In this experiment, one monitors the kinetics of proton transfer in condensed phase molecular systems, 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 $0.1\mu m$ which is equivalent to a temporal resolution of $0.3\text{ fs}$. Figure 9 is a schematic of this experimental setup.

3. A multi-channel high-voltage programmable waveform generator for manipulating piezoelectric transducers. This project is aimed at producing a 3D inertial drive slider in cryogenic SPM systems. Inertial sliders\(^10,11\) produce a series of discrete steps, each using one 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. Figure 10 is a picture of this experimental setup\(^12\).

9. Conclusions and Future Work

At first, the mechatronics laboratories were offered, at the college only to students majoring ME, and at the university to B.Sc. students who intended to specialize in experimental chemical physics (at the School of Chemistry). However, as these laboratories, both at 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 of AFEKA, however, in the near future AFEKA intends to establish an advanced program of interdisciplinary studies in engineering, where mechatronics will become a research focus and mechatronics studies will occupy a considerable part of the curricula of this program.

Acknowledgment

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References

1. S. Meek, S. Field and S. Davasia, ‘Mechatronic Education at the Department of Mechanical Engineering at the University of Utah’, *Mechatronics*, 13 (2003), 1-11.


Figure Captions

Fig. 1: The IO Drive 2000 power-interface board.

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

Fig. 3: A typical laboratory station, designed for the use of 1 or 2 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 figure, the compact external IO 2000 drive which contains the required power devices, and beneath, the compact box that contains the experiment setup for light intensity control.

Fig. 4: The experimental setup 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 setup is included in the text.

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

Fig. 6: A histogram that presents the number of students who attended the mechatronics courses over the years, 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.

Fig. 7: SolidWorks™ Designs of ongoing final projects: (Right) A macroscopic model of an SPM; (Left) A fruit firmness tester. The two designs are not the same scale. A detailed description of these designs is included in the text.

Fig. 8: The experimental setup for the characterization the linear stepper motor, prior to assembling it into the SPM. (A detailed description of this setup is included in the text).
Fig. 9: A schematic of the optical experimental setup 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 of this setup is included in the text).

Fig. 10: The experimental setup 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 of this setup is included in the text).
### Tables

Table 1: Cost analysis of equipment (per station)

<table>
<thead>
<tr>
<th>HARDWARE</th>
<th>PRICE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computer Desktop / Laptop - IBM / HP</td>
<td>~$1500</td>
</tr>
<tr>
<td>External power data acquisition board - IO Drive 2000 (Dedicated)</td>
<td>~$1350</td>
</tr>
<tr>
<td>Embedded board - PIC Evb (Dedicated)</td>
<td>~$350</td>
</tr>
<tr>
<td>Controlled components setups and accessories (Dedicated)</td>
<td>$700-$1800</td>
</tr>
<tr>
<td>100 MHz digital oscilloscope - Tektronix TDS 220 or compatible</td>
<td>In Laboratory</td>
</tr>
<tr>
<td>Function generator - Agilent 33120A or compatible</td>
<td>In Laboratory</td>
</tr>
<tr>
<td>Multi-meter - Tektronix TX3 or compatible</td>
<td>In Laboratory</td>
</tr>
<tr>
<td>Triple output power supply - OEM</td>
<td>In Laboratory</td>
</tr>
</tbody>
</table>
EPP Connector to PC
Buzzer
8-bit Digital Inputs & 2 Counter Inputs
Power Supply

CPLD CY37192
The heart of the board

12 bit DAC
12 bit ADC

2-Channel Power Amplifiers

Extra 8-Channel Analog Inputs

Analog In
Power Analog Out
PWM Out
8-bit Digital Out
±12V Out

8-bit Switch Inputs & Leds
Full Bride Power Drivers
12-bit Led Outputs & Automatic Fuses

Figure 1
16-Key Matrix Keyboard

8-bit Input Switches

2x16-Character LCD Display

8-bit Led Outputs

2-Channel 8-bit DAC

Cypress CY37128P84 CPLD – Implements all the board logic

ICSP Connector

Buzzer

MicroChip PIC16F877
8K Flash
256-byte RAM
128-byte EEPROM
5-channels 10-bit ADC
Synchronous UART
Asynchronous UART
I²C Communication Bus
Interrupt Controller
3 Counter Timers

Analog Outputs

External Bus

Timer Input

Analog Inputs

General Purpose 8-bit PORT C of the Microprocessor

Figure 2
Figure 4
Figure 5
Figure 6
Figure 9