Foundation Mechatronics Laboratory Course for Mechanical Engineering Students

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Abstract: This paper presents an assessment of recent development that targets an introductory mechatronics hands-on course taught within the mechanical engineering program at the United Arab Emirates University. In particular, the development attempts to enhance the students' cognitive as well as their psychomotor skills by integrating the knowledge taught in the lectures with the hands-on skills attained in the lab. Twelve well considered lab experiments were added to the lab manual of the course. Microcontroller-based experiments were introduced to walk students, who have never been exposed to microcontroller use before, through the learning journey using a number of mini projects. A survey among students to assess the development was conducted. It showed 63% of the 35 students strongly agreeing that, the course has trained them well in building microcontroller-based systems. It also highlighted the areas that still need further attention by the instructors.

1. Introduction

Mechatronics is the synergistic integration of mechanical engineering with electronics and intelligent computer control in the design and manufacturing of industrial products and processes [1]. It integrates sensors, actuators, signal conditioning, power electronics, decision and control algorithms, and computer hardware and software to manage complexity and communication in engineered systems. Mechatronics continues to play an increasing and expanding role in modern industry and is instrumental in their attempts to apply automation to industrial processes, and even in attempts to make the processes autonomous. Mechanical engineering students often come across a glass-wall between them and the multi-disciplinary Mechatronics and the introduction of the subject plays a critical role in developing them as competent mechatronic engineers. As one of the good mechanical students put it 'mechanical students are used to seeing things that they study, design and manipulate, while in Mechatronics they have to visualize or see it in the mind's eye only'. United Arab Emirates University is the top university in the country and has maintained its position since its inception more than 40 years ago. The top slice of the country's students joins the University. During their residence in the University, they not only study the specialization courses in their chosen discipline, but also take part in projects and competitions in several areas like aerospace, environment, renewable energy and Industry 4.0. The country is forward looking and progressive and has have few major advanced industries that provided employment to most of the graduates. In such an environment the authors felt the need for a foundation Mechatronics laboratory course that would introduce the building blocks and tools of Mechatronics in a practical way that would show the relationship between the theory and practice. Bloom's Taxonomy categorizes learning into three domains: cognitive (knowledge), psychomotor (skills) and affective (attitudes). With respect to Mechatronics the authors' hypothesis is that the psychomotor domain, developed mainly in the learning laboratory, greatly assists the mechanical engineering students in all three domains and to break the glass wall and become competent mechatronic engineers. To fulfil the need the aim and objectives were set in the following way:

Aim:
To provide the competence and confidence to (a) handle and explain mechatronic components, laboratory instruments and measurement systems, (b) carry out time and frequency response analyses, (c) differentiate analog and digital systems and (d) deal with microcontroller-based experimental applications, so that they can engage in the development of mechatronic system with the advanced courses to be studied later in the program.
Objectives:
The objectives of the course are to

1. Familiarize and consolidate the fundamental knowledge with hands-on work related to mechatronics measurement systems, components and their dynamics characteristics.
2. Build analytical and experimental skills in basic electronic circuits and their components, and their applications in mechatronics. This includes RCL circuits, diode circuits, transistor circuits, and operational amplifier circuits.
3. Familiarize the techniques of carrying out basic experimental analysis of time and frequency responses of dynamic systems.
4. Introduce the principles of the digital and discrete systems and how they are interfaced with the analog systems and signals, including the coverage of the sampling theory and the analog to digital and the digital to analog converters.
5. Familiarize with applications and use of microcontrollers in mechatronics measurement projects and experiments.

2. Literature review

Two main aspects that greatly assisted the formulation of the course are considered here. They are (i) the learning experience and pedagogy and (ii) breadth and depth of Mechatronics. The learning experience and pedagogy section describes the content and method of delivery of a course and how it influences the learning experience. The breadth and depth of Mechatronics presents a holistic view of Mechatronics and the selection of topics and coverage of sections for a foundation learning laboratory course.

2.1 Learning Experience and Pedagogy

In general, ‘Curriculum’ details what teachers are going to teach, or in other words, what learners are going to learn. In essence, it provides a formalized schema for the teacher, who then particularizes it to enable students to adapt from their existing framework of knowledge and skills to accommodate further knowledge and skills [2]. Pedagogy is the structuring of the learning in accordance with the curriculum, by the teacher to guide the learner through tasks that are just beyond current capability, and thereby building additional knowledge and skill. Pedagogical models vary from place to place and depends on the nature of the subject, background of students and facilities available among others. The Pedagogical Model by Victoria State Government [3] provides an overview of the learning cycle, and breaks it down into five domains or phases of instruction: Engage, Explore, Explain, Elaborate and Evaluate. The Pedagogical Model domains are elements of one complete model of teaching rather than separate, self-contained components. It provides enough flexibility so that in some lessons, students will move through all five domains while in other lessons, teachers will naturally switch between domains in response to student needs and learning program requirements. Mcleod [4] describes the zone of proximal development, ZPD, that refers to the difference between what a learner can do without help and what he or she can achieve with guidance and encouragement from a skilled partner. Thus, the term ‘proximal’ refers to those skills that the learner is ‘close’ to mastering. It distinguishes and connects the current or actual level of development of the learner and the next level attainable through the use of tools and facilitation by a capable adult. The authors believe that this area has to be considered carefully in the curriculum development so that the students’ initial reluctance and hesitation are designed out. They decided to adopt a hybrid model adopting and mixing Instructivism and Constructivism. Instructivism in this context places emphasis on the educator in control of what is to be learned and how it is to be learned, and the learner is the passive recipient of knowledge while constructivism emphasizes that people construct their own understanding and knowledge of the world through experiencing things and reflecting on those experiences [5].

2.2 Breadth and Depth of Mechatronics

Mechatronics, started as the application of control systems approach on mechanical systems incorporating pneumatics, hydraulics and electronics, has developed so rapidly to encompass every walk of life. A distinctive characteristic of mechatronic systems is the tight coupling between different technological fields, e.g. mechanics, hydraulics, electromechanics, pneumatics, electronics, computing and software. The microcontroller is an essential element in mechatronic systems, and the software content is currently developing rapidly. An important characteristic of the mechatronic devices and systems is their built-in intelligence that results through a combination of precision mechanical and electrical engineering and real-time programming integrated to the design process [6]. Modern mechatronics facilitates the development of products and systems that have new and novel technologies that are functionally integrated with information technology and software engineering. As Aboud and Haris [7] put it ‘A typical mechatronic system receives signals from the environment, processes them to generate new signals, which becomes inputs to actuating mechanisms, translating them into forces, movements and actions’. It has been said that an ideal mechatronic solution would be that where a deficiency of the mechanical system could be cost-effectively compensated by a suitable control engineering solution. The application areas of mechatronics include almost everything including robotic systems, automated manufacturing systems, aerospace engineering, bioinstrumentations. Because of these developments Mechanical Engineering students should be taught Mechatronics with intentions of application in the background rather than the components like diodes and transistors.

3. Description of the Course

The course catalog description of the course is stated as follows:

> *This course provides students with an introduction to mechatronics. Topics include: characteristics of mechatronics systems, review of measuring fundamental properties; transducers for motion measurements, fluid flow, temperature, pressure and strain, signal conditioning, operational amplifiers, diode circuits and applications, bipolar junction transistors and field-effect transistors theory and applications, analog to digital/digital to analog conversions, and microprocessor applications*.

In the instruction part, theories on analog circuits, including op amp circuits, and their applications, as well as digital systems are introduced. Measurement systems and the sampling theory are also taught in the lectures.

The course is designed such that the lectures precede the labs on the various topics in a progressive manner. Twelve lab experiments were devised to consolidate the knowledge that students were expected to gain during the lectures, and to establish their psychomotor skills in building experimental setups and using the lab instrumentations in mechatronics. After the introductory lab safety and orientation session, they start with basic voltage divider circuits including the use of potentiometers as input device. The complexity is increased gradually as students’ confidence in using lab equipment and instrumentations build up, and their mechatronics knowledge increased. The students are required to build and test various basic electronic circuits, such as diode circuits, transistor circuits, RC circuits, and op amp circuits. These gave them the familiarity and confidence on the components and measurement systems. During this time the students were also introduced and familiarized with measurement systems, and sensors and their calibrations.

Table 1 below lists the twelve lab experiments used in the course. The Arduino UNO board with its ATmega328 microcontroller is used in the last four labs. Introduction to the C programing language used for microcontroller, has been started with relevant introductory materials on digital systems. With minimal or no prior exposure to microcontroller use, the new development aims at developing students' ability to implement microcontroller-based applications with a target to prepare them to handle automation and measurement and control projects in future courses and the capstone project.

Table 1: The Scheduled lab experiments and Possible explanations

The Lab Experiments	Pressing Cause for this Experiment
Lab 1: Introduction to the lab instruments and equipment	Familiarize the students with safety and general rules of the lab as well as training them on the instruments and equipment
Lab 2: Voltage divider circuit and its applications	Students' first exposure to electronic circuit prototyping using breadboard by introducing voltage divider circuit and it's applications
Lab 3: Diode circuits and their applications	Introduce common diode circuits and application as a half-wave and full-wave rectifier and the effect of a filter capacitor in smoothing the output signal
Lab 4: Bipolar junction transistor circuits	Understand (BJT) transistor and its operating regions in addition to its applications and analysis, including using it as a solid-state switch and as an inverter.
Lab 5: First order system analysis and applications	Introduce students to experimental analysis and study of first order dynamic systems, perform time and frequency response on RC circuit, implement a first order RC low pass filter as an application.
Lab 6: Operational amplifier and its applications	familiarize students with the Op Amp functions, characteristics, limitations and applications, including voltage follower, inverting, noninverting circuits, and integrator,
Lab 7: Introduction to sensors 1	Introduction to several sensors used for measurement and understand the required signal conditioning (amplification, filtering) in addition to calibration
Lab 8: Introduction to sensors 2	
Lab 9: Introduction to Arduino UNO - digital I/O	Introducing microcontroller and programming with the Arduino UNO development board. Familiarize students with Arduino Digital I/O functions, Analog I/O and digital port manipulation.
Lab 10: Introduction to Arduino UNO - analog I/O	
Lab 11: Analog signal measurement using the Arduino	Using Arduino board as a data acquisition device to log temperature measurement from a thermocouple, design and implement a digital filter to filter noisy sensor data in addition to calibration

Lab 12: Open loop motor speed control and measurement using the Arduino	The last experiment aim to introduce the integration of hardware and software in mechatronics control projects through a case study on open loop speed control of a DC motor using Arduino and Opto-switch encoder for speed measurement.

3.1 Examples from the twelve lab experiments

This section describes representative examples and lessons from the twelve lab experiments that are performed in the course.

3.1.a Diode Circuits and their Applications

Half wave rectifier and full wave rectifier circuits that employ diodes to remove and invert the negative half of the waveform were introduced first in the lecture, and then constructed and tested by the students in the lab to experimentally verify the relevant science and properties of diodes. A full wave rectifier circuit that consists of light emitting diodes (LED), shown in Figure 1, is used to see the concept through visualization. The circuit is driven by a square wave signal from a function generator. The frequency is kept low to allow the students to see the blinking of the red and green pairs of LEDs and the full wave rectification effect.

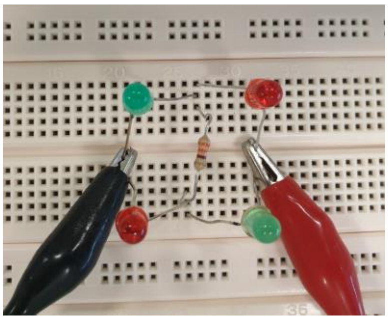

Figure 1: Full wave rectifier consisting of LEDs

3.1.b First Order Low-Pass filter design using RC circuit:

The frequency response of dynamic systems is typically covered as part of a dedicated course on system dynamics. In the authors' department the topic is initially covered in the introductory mechatronics course and then covered in more details in a course on dynamics systems and control. With such brief coverage in this course, it is important to present the topics in the most convincing way. As an application on the system dynamic response, which is covered in the lecture, the students in the lab experiment with a first order analog low pass filter consisting of a resistor and capacitor (R-C circuit) as shown in the schematic in Figure 2.

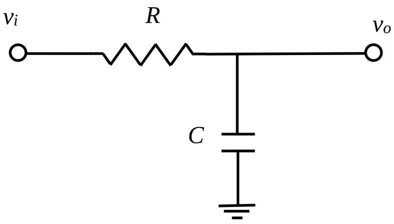

Figure 2: R-C circuit schematic

The function generator is used to output a sinusoidal signal with superimposed noise signal as shown in Figure 3. Students select the corner frequency by appropriately choosing the values of R and C of the low-pass filter to reduce the noise in the output signal as well as to keep the amplitude ratio and the phase, close to one and zero respectively. Figure 3 shows a typical input output signals using such an analog low-pass filter.

3.1.c Lighting an LED with push button press:

Since this course represent the first exposure to microcontrollers, the topic is introduced to students gradually in the lectures and lab. Using the circuit shown in Figure 4 students learn how program the microcontroller to generate output signal that lights up an LED, and read an input digital signal from the push button. Students learn how to implement different scenarios for the setup. For example pressing the button, causes the LED to toggle between on and off status.

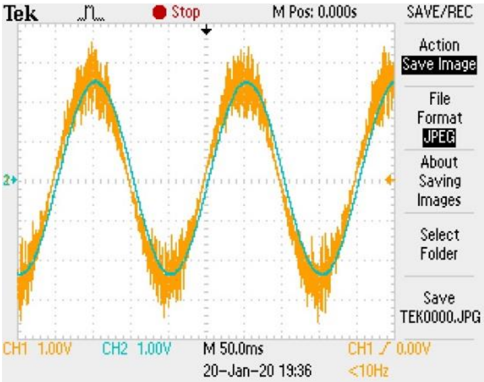

Figure 3: Input output of analog low pass filter, R = 4.7 KΩ, C = 1.5 μF, f = 5Hz, Amplitude = 5V

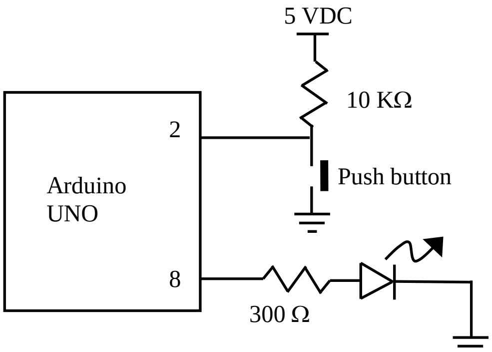

Figure 4: Arduino digital input-output example

3.1.d First Order Low-Pass filter design and implementation using the Arduino:

As a real application of microcontrollers, students use the Arduino to implement a digital low pass filter that is used to filter out the noise from a sine waveform signal that is corrupted by noise. Students learn first how to discretise the first order differential equation representing the low pass filter, which is written here as

$$u = \tau \frac{dy}{dt} + y \tag{1}$$

It is then discretized using the forward difference method to yield

$$u(n) = \tau \frac{y(n+1) - y(n)}{T} + y(n) \tag{2}$$

Equation (2) is rewritten compactly to obtain a form with minimum number floating-point operations, as indicated below

$$y(n+1) = \propto u(n) + \beta\, y(n) \tag{3}$$

where α and β are constants that can be obtained from τ and T. The Arduino code that implements the method is shown in Figure 5, and the input and output signal data are collected through the serial communication link and plotted using Matlab.

```
int A;
float conv_factor, U, Up, Y, Yp, T, tou, alpha, beta;
void setup()
{
  conv_factor = 5.0 / 1023.0;
  Serial.begin(115200);
  A = analogRead(0);
  Up = (float) A * conv_factor;
  Yp = Up;
  T = 0.001;
  tou = 0.05;
  alpha = T / tou;
  beta = 1.0 - alpha;
}

void loop()
{
  A = analogRead(0);
  U = (float) A * conv_factor;
  Y = alpha * Up + beta * Yp;
  Yp = Y;
  Up = U;
  Serial.print(U);
  Serial.print(" ");
  Serial.println(Y);
  delay(1);
}
```

Figure 5: Arduino code for implementing low pass filter

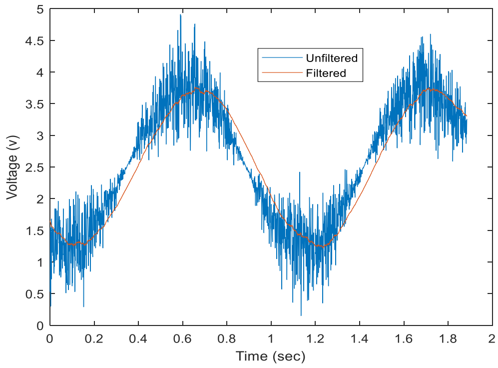

Figure 6: Input output of digital low pass filter

Figure 6 shows the noisy sine wave signal and the output filtered signal obtained using the digital low pass filter. As with the analog low pass filter a small phase shift was introduced by the dynamics of the first order low pas filter.

3.1.e Motor speed measurement using encoder:

This task culminates the microcontroller use in the course. Students interface the setup shown in Figure 7, to drive the motor in open loop fashion using a PWM step input signal from the Arduino which is used to switch the TIP41 transistor that drives the motor as illustrated in Figure 8. They also implement an encoder interfacing algorithm to read the corresponding speed of the motor. The setup is developed in-house, where the encoder disc is cut to have 20 slots. It is used to generate square pulses by interrupting an infrared LED light that triggers a phototransistor, shown in Figure 9, to generate the square pulses.

The algorithm is developed to count the number rising and falling edges of the generated square signal that elapsed every 100 milliseconds. The speed is estimated as number of counted edges per 0.1 sec, and could be converted subsequently to angular speed units like RPM or rad/sec. Serial communication with the PC is used to send the estimated speed data every 100 msec. The result is plotted as open loop step response of the DC motor system as shown in Figure 10.

Figure 7: DC motor with encoder

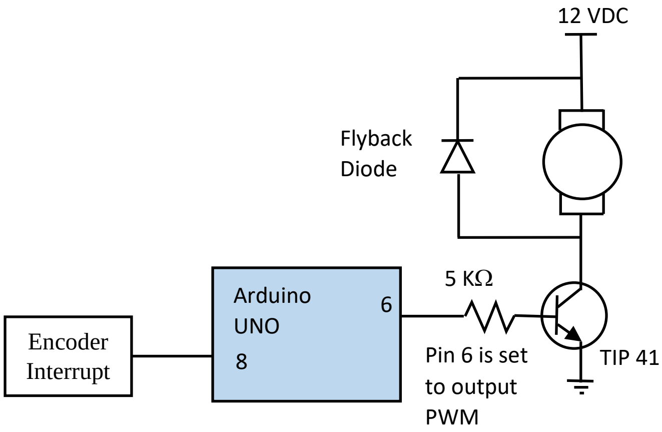

Figure 8: DC motor driven by Arduino

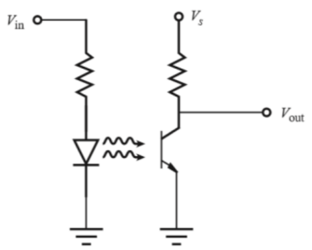

Figure 9: Phototransistor optical interrupter

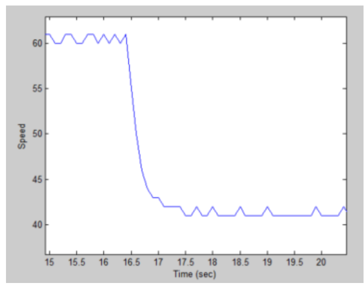

Figure 10: Open loop step response of DC motor system

4. Observations while Conducting Classes

Compared to previous offerings of the course, that involved fewer experiments involving diodes and transistors' characterizations, frequency response of RC circuits, and LabVIEW based measurements, most students showed considerable interest and enthusiasm in the new lab experiments in the current offering. Their interaction with the instructors and their body language showed clear signs of the effectiveness and appropriateness of the used labs and methods.

5. Student Reflection of the Course

Thirty-five out of forty undergraduate students, who were enrolled in the course in Fall 2019, responded to the course survey that consisted of eight statements with five provisions of reflections to choose from: (a) strongly agree (b) agree (c) neutral (d) disagree and (e) strongly disagree. The following subsections considers their responses.

5.1 Statement S1

The hands-on work with basic electronic components and the standard instruments in the laboratory made me feel comfortable with the theory and applications of the components

Reflection	Number of Students	Percentage
Strongly agree	18	51.4
Agree	14	40
Neutral	3	8.6
Disagree	0	0
Strongly Disagree	0	0

This statement refers to the question whether recognition and familiarity of the basic electronic components and the standard instruments should be included to consolidate the theoretical knowledge. Nearly 51% strongly agreed while another 40% agreed. This endorses the inclusion of these experiments and indicates the necessity for consolidating this approach.

5.2 Statement S2

The experiments with the RCL network systems greatly enhanced my understanding of dynamic systems

Reflection	Number of Students	Percentage
Strongly agree	7	20
Agree	21	60
Neutral	7	20
Disagree	0	0
Strongly Disagree	0	0

This statement refers specifically to the inclusion of the RCL circuits. The results show that the students while recognizing the benefit with 7 strong agreements and 21 agreements, they express their lesser amount of gain than the previous one.

5.3 Statement S3

The theory of the digital and discrete systems, logic gates, mathematic logic and the basics of microcontrollers introduced in this course is consolidated well by the purpose built lab experiments

Reflection	Number of Students	Percentage
Strongly agree	6	17.1
Agree	17	48.6
Neutral	11	31.4
Disagree	0	0
Strongly Disagree	1	2.9

Although nearly 50% agree with the statement, about the third were neutral indicating reservation and hinting to room for improvement.

5.4 Statement S4

The theory relating to binary, decimal and hexadecimal representations, and relating them to digital systems, microprocessors and their programming, were greatly enhanced by the purpose built lab experiments

Reflection	Number of Students	Percentage
Strongly agree	15	42.9
Agree	14	40
Neutral	4	11.4
Disagree	1	2.9
Strongly Disagree	1	2.9

5.5 Statement S5

The course introduce me to the measurement systems, and signal conditioning and processing, and the applications of the analog to digital converters to acquire analog and digital signals from various transducers and sensors.

Reflection	Number of Students	Percentage
Strongly agree	13	37.1
Agree	14	40
Neutral	8	22.9
Disagree	0	0
Strongly Disagree	0	0

5.6 Statement S6

The course trained me well on building microcontroller based digital systems that perform simple tasks like lighting an LED and responding to a push-button press.

Reflection	Number of Students	Percentage
Strongly agree	22	62.9
Agree	11	31.4
Neutral	2	5.7
Disagree	0	0
Strongly Disagree	0	0

This statement refers to the introductory microcontroller training in the course. Nearly 63% strong agree, and 31% agree as a clear indication of students' success in breaking glass-wall between them and the use of microcontrollers.

5.7 Statement S7

The course allowed me to train on building measurement systems that integrate microcontrollers, sensors and signal conditioning and processing units to acquire data for feedback closed loop control.

Reflection	Number of Students	Percentage
Strongly agree	5	14.3
Agree	20	57.1
Neutral	10	28.6
Disagree	0	0
Strongly Disagree	0	0

5.8 Statement S8

I am confident to build a mechatronic system that contains microcontrollers, sensors and other electronic components to perform specific functions.

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Reflection	Number of Students	Percentage
Strongly agree	6	17.1
Agree	14	40
Neutral	14	40
Disagree	1	2.9
Strongly Disagree	0	0

The 40% neutral responses could be an indication of hesitation for using microcontrollers in fairly advanced applications.

6. Analysis and Conclusions

The result of the students' survey as given in Table 2 shows, the responses to the eight statements vary to some extent but heavily inclines towards agreeing with the statements rather than to disagreeing. In statements like S1, there is clear agreement with the respective statement, whereas for statements like S3, S7 and S8 there seem to be some hesitations to agreeing with the statements, which are indicated by the number of neutral responses. Statement 3 indicates the need to further support the students in the learning process. The author group has taken note of this for further improvement. Statements S7 and S8 are more ambitious for a Foundation Mechatronics lab course but were included to find out and to see whether there are negative feelings or signs of the glass wall appearing. In that sense they are good results.

Table 2: Results of the students' survey

	S1	*S2*	*S3*	*S4*	*S5*	*S6*	*S7*	*S8*
Strongly Agree	18	7	6	15	13	22	5	6
Agree	14	21	17	14	14	11	20	14
Neutral	3	7	11	4	8	2	10	14
Disagree	0	0	0	1	0	0	0	1
Strongly Disagree	0	0	1	1	0	0	0	0

6.1 Conclusions

In the light of the survey it is safe to conclude the following:

1. The course is structured well to train building microcontroller based digital systems that perform simple tasks like lighting an LED and responding to a push-button press. This was strongly agreed by 22 students and agreed by 11 students. Only 2 students stayed neutral.
2. The hands-on work with basic electronic components and the standard instruments in the laboratory is a very good method to make the students to feel comfortable with the theory and applications of the components. 18 students strongly agreed, 14 students agreed and only 3 students stayed neutral.

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