EXPERIENCES FROM RUNNING A "HOME-BREW" LABORATORY COURSE AND SETTING UP A NEW STUDENT MEASUREMENT SESSION FOR THE EDUCATION OF SENSORICS

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Abstract: This paper summarizes the experiences that accumulated during the 10 semesters of education of the course titled "Physics of Sensors", and presents a new student experiment for the training at ultrasonic proximity sensors at our sensorics student laboratory. The described pitfalls, needs, misconceptions, ineffective experiments helped to improve this laboratory course. Following the principles used during the creation of the student laboratory experiments, the presented modifications and new setup are implemented in a manner suitable for re-creating and modifying by the inexperienced student or the recently graduated bachelor at hobby or at work.

Keywords: *physics of sensors, sensorics, sensor education, ultrasonic sensors, HC-SR04*

I. INTRODUCTION

Since the academic year of 2012/2013 the students at the GAMF Faculty of Engineering and Computer Science of the John von Neumann University (formerly Kecskemét College) have the opportunity to take the course named "Physics of Sensors", which consists of lectures and student laboratory work, both 2 classes weekly. The lectures provide basic theoretical knowledge in the field, while the student laboratory is intended to familiarize them with basic sensor circuitry and the use of modern compact industrial sensors. The course is obligatory for the computer engineering students in "industrial informatics and microcontrollers" specialization and for the mechanical engineering students in mechatronics specialization [1].

There are conclusions to draw from the first few years of the laboratory part of the course. These affect the introductory training for the lab work, the deletion or change of certain parts of the exercises compared to the original [2], and the introduction of new laboratory exercises as well (one so far, discussed in the III. section).

II. EXPERIENCES WITH THE OLDER STUDENT LABORATORY SESSIONS

All experiments are the design and build of our department, because it was not possible to find sets of pre-built laboratory sessions at sensor education. The following subsection numbering is also intended to refer to the numbering of the sessions in [2].

II.0 Introductory session.

Session description: Work safety training. Evaluating measurements. Measurement errors, and the laws of error propagation. The basics of regression calculus. [2]

Experiences, improvements: Fortunately, there were no accidents affecting human health in our laboratory so far. A few damages to electronics have occurred, mainly because the students sometimes — contrary to the syllabus — switch on circuits without having checked them by the instructor.

Good laboratory protocols mostly contain the measurement principles, this is required at this course too, moreover it is recommended for the students to describe the principles in advance as a homework. In the first semesters of the course, the students felt obscure, what the measurement principles are, many of them simply copied (sometimes as images!) the lead-in part of the syllabus.

Therefore, for a few semesters, the students are informed at the introductory laboratory session that it is satisfactory to answer five questions: What quantities are varied during the exercise, and how? What quantities are measured, and how? What quantities are calculated from measurements, and how? What data are plotted, and as the function of what? If there is some statistical evaluation (e.g. linear regression), what is the meaning of the resulting parameters? Since then, the quality of the measurement principle resumes underwent dramatic improvement.

II.1 Temperature measurement with resistance thermometers and II.2 Temperature measurement with thermistors.

Description: Cross-calibration of Pt100 or NTC thermistor (respectively) to a monolithic IC temperature transducer while varying temperature with Peltier elements [2].

Experiences, improvements: These exercises are well established, the students have no systematical difficulties with them.

For a few semesters the students are allowed to use higher voltage setting (and current) for the heating and cooling with Peltier elements, than originally planned (5,1 A at 4,6 V instead of 2,9 A at 2,9 V, which is achieved by using the 5 V output on the power supply instead of the 3,3 V output). This improved the execution time of data collecting from approx. 25 min to 12 min.

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II.3 Bridge circuits.
Session description: Assembling Wheatstone bridge circuits with pressure force sensors under the legs of a tablet. Measuring bridge characteristics while moving a weight on tablet [2].

Experiences: The CP149 pressure force sensors used for studying the sensitivity of the quarter, the half and the full Wheatstone-bridges, have a strong nonlinear behavior [3]. This nonlinearity affects the bridge characteristics, the quarter bridge at most (Fig. 1.a).

Many of the students worry about the shape of the characteristics in the beginning, and they need confirmation if they carry out the measurement well. Later they can see, that the half bridge shows less nonlinearity (Fig. 1.b), and the full bridge even less (Fig. 1.c).

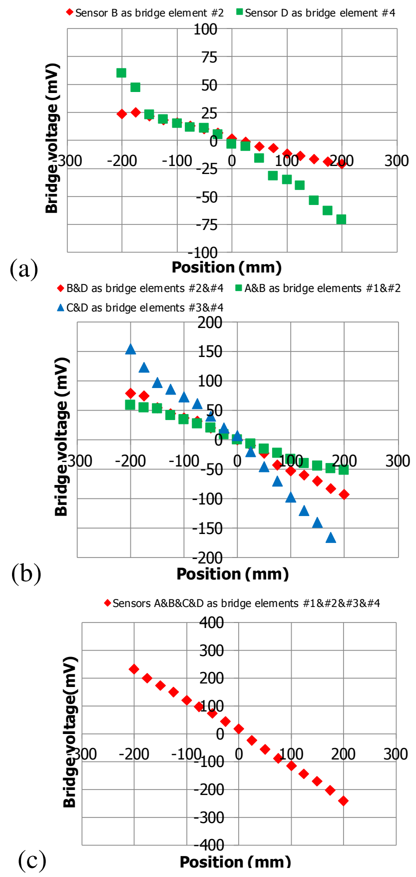


Figure 1. Characteristics of (a) the quarter, (b) the half and (c) the full Wheatstone bridge

I decided not to choose other sensor with smaller nonlinearity, because the tendency of more sensors towards a linear characteristics is interesting in itself too.

II.4 Comparing the 2- and 3-wire bridges.
Session description: Measuring Wheatstone bridge characteristics while the temperature of the long wires connecting the sensor is varied (modeling environmental effects and their elimination) [2].

Experiences: It proved rather cumbersome to handle the hot and the cold ice gel that varies the temperature of the long wires. The microwave oven and the refrigerator that enabled these are one floor away, and during the measurement the temperature of the ice gel dropped or raised towards the ambient temperature. Therefore the students found this experiment neither convenient nor convincing.

These were the main causes, why this experiment was selected to discontinue in favor of the newly developed ultrasonic proximity measurement (see the next section).

II.5 Measurement of fluid level and hydrostatic pressure.
Description: Varying water level in a vessel, and measuring pressure sensor output voltage amplified by an instrumentation amplifier at multiple amplification settings [2].

Experiences: One of the two pitfalls at this measurement for the students is recording the fluid level only in the vessel, not in the pipe leading to the sensor, although the pressure is determined by the level difference. The other one is the bad assumption of value change of the amplification setting potentiometer suggested by the turning direction. The instructor must notice these and warn the students in time. Otherwise this experiment proved to be robust and straightforward.

II.6 Capacitive proximity sensing.
Description: Measuring the capacitance change caused by insulator thickness and position change inside a capacitor, and by the water level change inside a capacitor [2].

Experiences, improvements: While the effect of varying water level on the capacitance inside the bottle with capacitor armatures is always impressive for the students, the effect of moving plastic insulator parts inside a capacitor model is on contrary too small, not convincing enough. So that part of the exercise was dropped in favor of a new compact industrial capacitive sensor, the LJC30A3 (Fig. 2.).

The students can record the switching distance of the sensor in the case of several test objects, mainly liquids (water, ethanol, mineral oil, empty plastic bottle, etc.). Unfortunately, there is no data to plot against the distance, as the LJC30A3 has no analog output, so I continue the search for an affordable capacitive proximity sensor with analog output, or a modification possibility of the LJC30A3, that enables this.

Figure 2. The new capacitive proximity sensor in combination with a specimen of ethylene-glycol

II.7 Magnetic proximity sensing.
Session description: Measuring the switching distance of a Reed switch and an inductive proximity switch in the case of different magnets and metal samples, respectively. Measuring the output signal of an analog output inductive proximity sensor as the function of distance from various

metal samples [2].

Experiences: This exercise has no problems from the sensorics or electronics point of view, although care should be taken, how the students measure the distance between the sensor and the test objects moved by a vice (similar to Fig. 2.) using a caliper. Sometimes they try to measure with sub-mm accuracy while holding the caliper in hand with no support in position and angle. Then the instructor has to suggest them to measure the distance between the vice jaws, where there are appropriate grooves for support, and subtract the jaw distance at touching sensor and object from the jaw distance at the sensor and object position in question.

II.8 Optical proximity sensing.

Session description: Measuring the output signal of analog output optical sensors as the function of distance from objects of different colors, surface roughness etc. [2].

Experiences, improvements: The students had difficulties with the placing of specimens into the infrared (invisible) light beam, therefore recently they are given an infrared viewer in order to find the beam easier.

III. CREATING THE NEW LABORATORY SESSION

III.1 Motivation and sensor choice.

Since the beginning of our sensorics laboratory course, many students expressed their interest in ultrasonic proximity sensors, and their regret about the lack of a lab session about them.

As several of the interested students are Arduino-hobbyists, I decided to introduce an experiment using the HC-SR04 sensor (Fig. 3) that is widespread for DIY experiments and applications with Arduino control and readout. My intention was also to show its behavior with other electronics than Arduino.

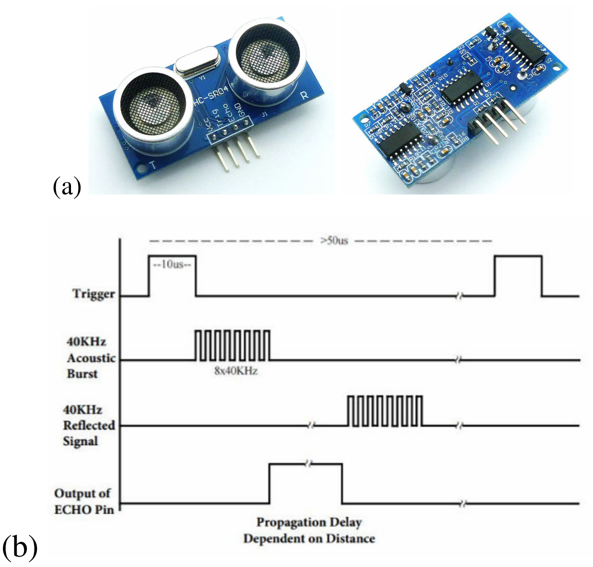


Figure 3. The appearance (a) and the timing diagram (b) of the HC-SR04 sensors used in the lab exercise [4]

The HC-SR04 is in the form of a small (W×H×D = 45 mm×20 mm×15 mm) printed circuit board (Fig. 3.a). It is easy to recognize from its biggest two parts: an ultrasonic transmitter and a receiver. It has four male connector pins, two of them provide power [#1: Vcc (nominally +5 V) and #4: GND], the other two are the so called *Trigger* input (#2) and the *Echo* output (#3).

The *Trigger* input requires a TTL pulse at least 10 μs long (Fig. 3.b). Having received the trigger pulse, a microcontroller in the HC-SR04 sends an ultrasonic pulse burst of 8 pulses through the transmitter (with ultrasonic frequency of 40 kHz). At the same time it sets the *Echo* output to *TTL high*. Then the controller waits for the reflected ultrasound pulse train. When it arrives (or a timeout period elapses), the *Echo* output is set to *TTL low* again. Before the next such measurement a minimum 50 ms interval is necessary. The Echo output so delivers square TTL pulses with temporal width that is proportional to the distance of the reflecting obstacle (namely twice the distance divided by the sound speed) [4].

Usually HC-SR04 users employ an Arduino digital output to generate the trigger pulse, and an input pin of the same Arduino to measure the time duration of the *Echo* pulse length with digital timing.

III.2 The experiment setup.

The main bulk part of the experimental setup is an otherwise unused old optical rail of wood (0 in Fig. 4). The optical element carriers belonging to the rail were slightly modified (in a reversible manner) to accept the HC-SR04 sensor modules (1, 2 and 3 in the Figure). The reflecting obstacle was formerly an optical screen (4 in the Figure).

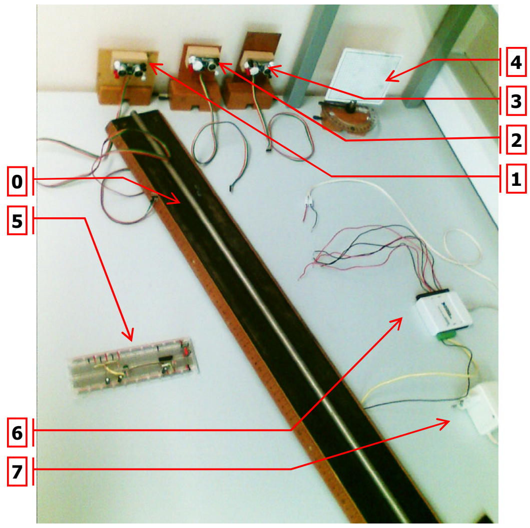


Figure 4. View of the test stand of the ultrasonic proximity sensing exercise.

Three HC-SR04 sensors are employed in the laboratory session, one of them (sensor #1) is full-featured that is, it can be used for both transmitting ultrasound and measuring the reflection (this is also referred to as *two-way* ultrasonic proximity measurement, because the ultrasonic pulses travel the same distance twice between emission and reception), or for just transmitting ultrasound (in this case its *Echo* output is omitted). The other two modules (sensors #2 and #3) can be only used for signal reception, as their transmitter is mechanically blocked (by putty glue). The electronics is not involved, moreover in order the *Echo* output to function correctly, the same *Trigger* input is connected that starts the transmitter (logically this can be referred to as a *one-way* ultrasonic proximity measurement).

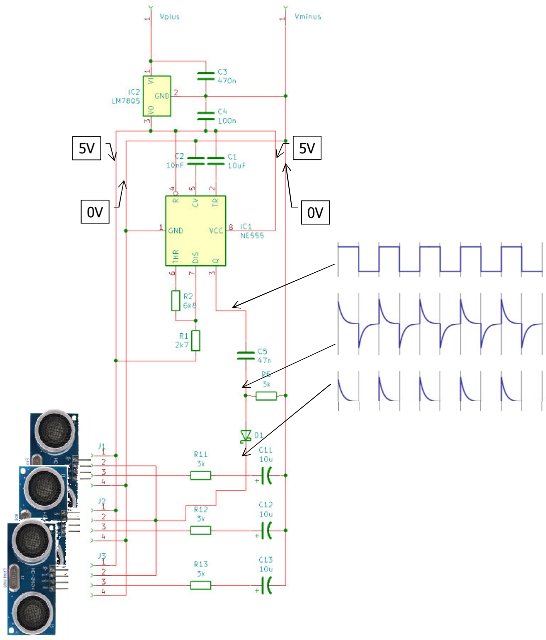
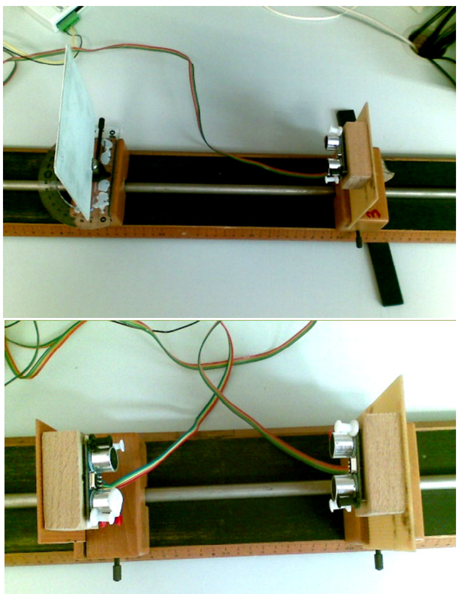


Figure 5. The operating circuit of the ultrasonic proximity sensing exercise.

The essence of the laboratory session is to observe and measure the output signals of ultrasonic proximity sensor(s) while varying its (their) distance from a reflecting obstacle (in Fig. 6.a sensor #1 transmits to/receives from the screen) or from an ultrasound source (in Fig. 6.b sensor #1 transmits to sensor #2; in Fig. 7 sensor #1 transmits to #2 and #3).



(a)

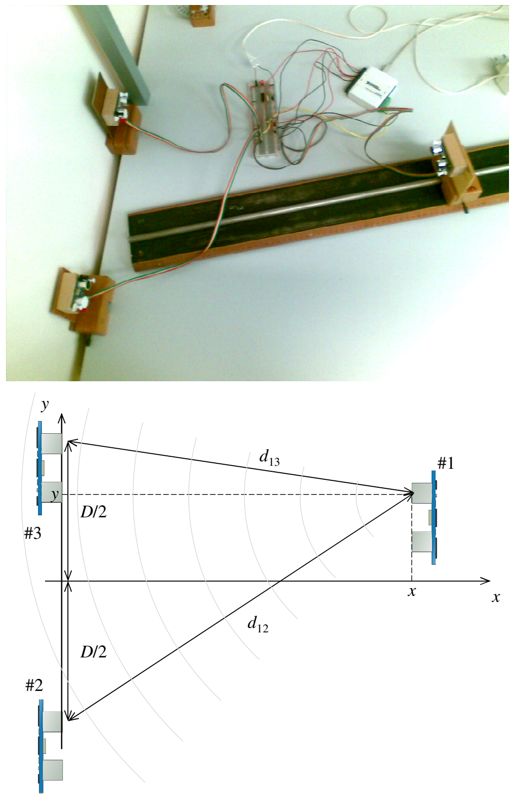
(b)

Figure 6. (a) Two-way and (b) one-way proximity sensing setup

The electronic circuit built to operate the HC-SR04's (5 in Fig. 4) is detailed on Fig. 5. The generation of the trigger pulses begins using a 555 timer IC set to astable mode [4]. The complementary discrete components, resistors, capacitors are chosen to have a pulse period longer than the 50 ms recovery interval of the HC-SR04 [T=ln 2·C_1·(R_1+2·R_2)≈0.693·10 µF·(2.7 kΩ+2·6.8 kΩ)≈ ≈ 113 ms]. The length of these pulses is several orders of magnitude longer than the nominal 10 µs given by the documentation [T_{high} = ln 2·C_1·(R_1+R_2) ≈ 0.693·10 µF·(2.7 kΩ+6.8 kΩ) ≈ ≈ 65.8 ms], so the actual trigger pulses are formed by differentiating the edges in the pulse train of the 555 (the negative pulses are eliminated using the diode after the differentiating RC part). The suitable R_5 and C_5 values were determined experimentally, so that the pulse peak is approximately 3.5 V and the FWHM is 200 µs.

The path of the trigger pulse train is divided into three, all of them lead to four-pin female connector slots, where the three HC-SR04 modules can be plugged in. The *Echo* outputs of each HC-SR04's are linked to integrating RC-combinations.

For data acquisition a NI USB-6008 DAQ module is employed (6 in Fig. 4), the first three differential analog inputs read the voltage at the points of interest (see below), and this data is further processed and visualized by a LabVIEW program running on a PC.



(a)

(b)

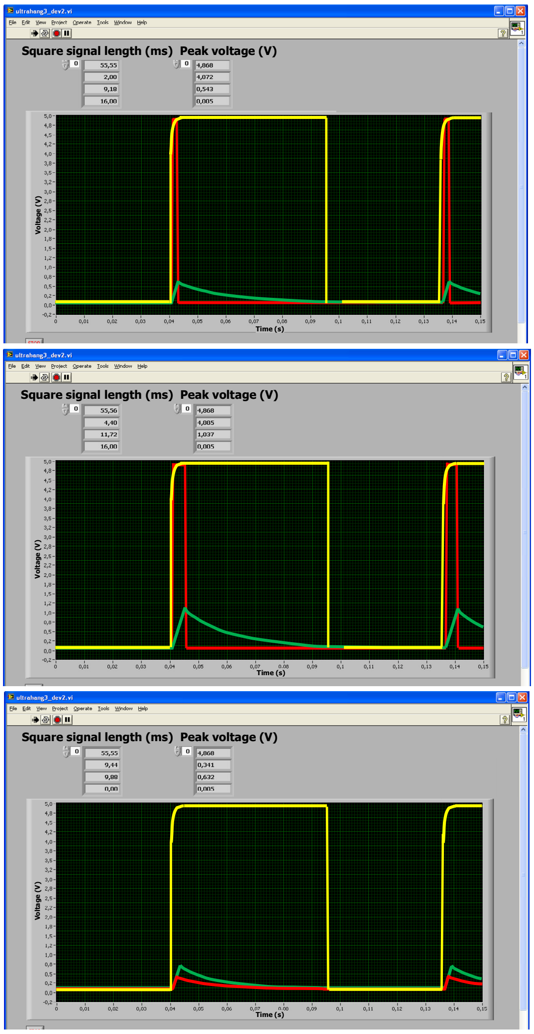
Figure 7. Setup for simultaneous one-way ultrasonic proximity sensing using one transmitter on the rail and two receivers off-rail. (a) View of the experiment. (b) Definition of the symbols used.

III.3 The process of the student exercise.

The first hands-on task of the students is to properly plug the power supply to the board according to the circuit schematics. The wire coloring on the panel and in the documentation helps this, and all the following connections.

Then follows the experiment depicted on Fig. 6.a. This requires plugging of the first HC-SR04 into the first connector slot and the wires between the measuring points and the DAQ card: the voltages of interest are the pulse train of the 555 IC, the *Echo* output of the HC-SR04 #1 and the integrated signal of the latter. The DAQ card also needs to receive the same trigger from the trigger wiring, as the ultrasonic sensors.

After starting the LabVIEW program and powering up the circuit, the students see the three voltages of interest as waveforms on the screen (Fig. 8.).



(a)

(b)

(c)

Figure 8. The front panel of the LabVIEW virtual instrument for data processing and visualization of the ultrasonic proximity sensing exercise. (a) Shorter echo time. (b) Longer echo time. (c) During the triangulating experiment: both receivers are in operation, and their integrated Echo pulses are measured

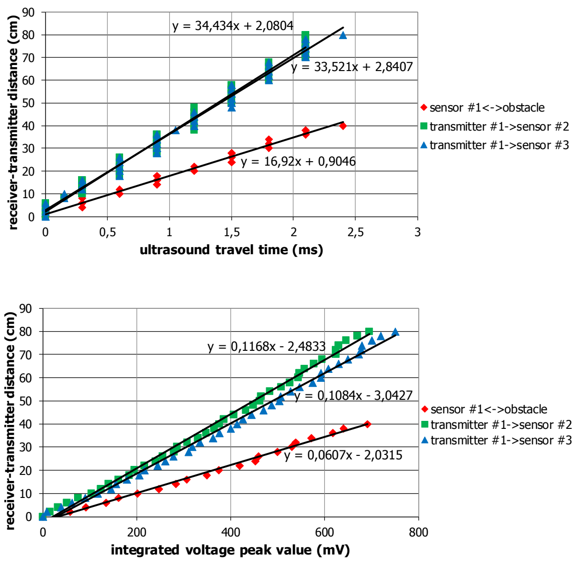
The program also prints the temporal width and the peak voltage of every waveform. The students' attention is drawn to the fact that a square waveform in red (an *Echo* output pulse) begins at every rising edge of the yellow waveform (the 555 IC pulse train). The green waveform is the integration of the *Echo* output (red) signal. As familiarizing with the setup, the students are recommended a short playing around with the distances of the sensor and the reflecting screen.

During this, they must notice the advantage of reading the peak voltage of the integrated waveform over the reading of the temporal width of the *Echo* output voltage: as the DAQ card's highest sampling frequency is limited (10 kHz summed for all sampled channels, and there are 3 sampled channels), the measured values of the temporal length change in quanta of 3/10 kHz = 0.3 ms. Supposing the sound speed to be 340 m/s in the environment, the measured temporal length changes only for a minimum distance change of 1/2·340 m/s·0.3 ms ≈ 5 cm.

Contrary to this, the peak voltage changes at much smaller distance variations.

The students are required to measure both the temporal length of the signal at the *Echo* output, and the peak voltage of the integrated signal at different distance settings. The data is then plotted on two graphs: both with the distance on the *y* axis, and the temporal length/peak voltage on the *x* axis (Fig. 9. red plots). The students' attention is drawn to the slope of the first plot: they get it mostly in the units of cm/ms or mm/ms. They have to convert it into m/s, and recognize the half of the speed of sound. The slope of the second plot is computed for later purposes (for calculating distances from peak voltages) too.

The next part of the laboratory exercise is about the one-way sensing setup (Fig. 6.b), which is carried out with many similarities to the two-way part.



(a)

(b)

Figure 9. Plots of example data from the two-way and the one-way sensing setups: distance as the function of (a) echo pulse length (b) peak voltage of integrated waveform

First the students have to disconnect the circuit from the power, and the DAQ card from the computer. Then ultrasonic sensor #2 has to be connected and the DAQ measuring wires have to be placed to measure the length of the *Echo* output and the integrated output of sensor #2 instead of sensor #1. After these, the DAQ card can be connected again to the computer, and the circuit powered up again.

The students have to repeat the previous measurements, this time varying the distance between sensor #1 (used only for transmission) and #2. The data must be inserted into the previous graphs (Fig. 9., green plots). Their attention is drawn again to the slope of the first plot, this time it is the speed of sound.

After measuring the relation of transmitter #1–receiver

#2, the relation of transmitter #1–receiver #3 must be measured too (Fig. 9., blue plots). The students must notice, that the different slopes of the integrated peak voltage–distance plots can be the consequences of the different values of the integrating circuit parts.

The last main part of this laboratory session is the simultaneous distance measurement of the transmitter (sensor #1 again with its output omitted) from both receivers. This is done in order to see, how the position of the transmitter moving in a plane can be determined by triangulation.

With the usual caution, all sensors must be connected to the circuit, and the DAQ card is set to measure the integrated waveforms from sensors #2 and #3, while these sensors are placed off-rail at a fixed distance from each other (ca. 40 cm, this is the baseline of the triangulation, denoted by D on Fig. 7.b). The transmitter is placed at different points on the rail (Fig. 7). The distances d_{12} and d_{13} have to be determined from the peak voltages using the linear functions regressed previously to the peak voltage–distance plots in the two-way experiments (Fig. 9.b green and blue plots). Taking into account the rectangular triangles in Fig. 7.b, using d_{12}, d_{13} and D, the students can calculate the (x, y) coordinates of the transmitter and plot its trajectory (Fig. 10.).

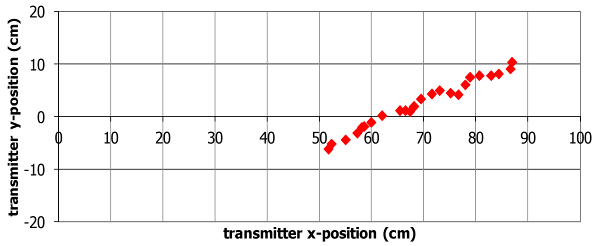


Figure 10. Plots of the resulting example data from the triangulating experiment: the trajectory of the transmitter (sensor #1) in the coordinate system defined on Fig. 7.b

The students have to notice, that as the transmitter approaches the receivers, the measurement data will be uninterpretable beyond a point, because the ultrasound is emitted in a finite angle cone, and first one of the receivers, then both of them will be outside the cone. At the same time, there is a tradeoff between the measurable plane section size and the accuracy of the trajectory measurement: if the baseline between the receivers increase, so increases the accuracy, but one of the receivers will fall outside the ultrasound emission cone earlier, and vice versa.

IV. RESULTS

Since 2012 the course was taken by 177 students, of whom 176 fulfilled it. The histogram of the students' final score in percent is shown in Fig. 11.

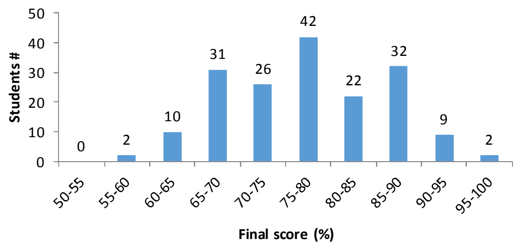


Figure 11. Histogram of the students' final score in %

There were no students with score under 50 %, which imply, that the course can be accomplished by any average capability students.

The average score of the individual lab sessions in percent is shown in Table 1.

Table 1. Average score of the individual lab sessions

Session topic	Avg. score (%)
Resistance thermometer	83.1%
Thermistor	83.8%
Comparing the ¼, ½ and full bridges	87.0%
Comparing the 2- and 3-wire bridges	74.1%
Pressure and fluid level measurement	87.5%
Capacitive proximity sensing	94.4%
Magnetic proximity sensing	94.7%
Optical proximity sensing	97.7%
Ultrasonic proximity sensing	89.6%

From the demonstrability and the convenience point of view, the "Comparing the 2- and 3-wire bridges" session was selected for discontinuation. As the average scores show, the students were also the weakest at this experiment. The replacement session ("Ultrasonic proximity sensing") proved to be the hardest among the proximity sensor sessions (from the scores point of view), but even so, the students are better at this, than at any of the first five topics, that aim basic sensor circuitry.

The number of students with the particular grades is shown in Table 2.

Table 2. Distribution of final grades

Grade	Not fulfilled	E	D	C	B	A
# of students	1	0	2	67	64	43

V. CONCLUSIONS

Laboratory exercises have been newly created, discarded and modified in hardware or at least in student tutoring to match the needs, the strengths and the weaknesses of the students. This work has been carried out using local ideas and simple, cost effective parts, and is planned to be regularly iterated.

VI. ACKNOWLEDGEMENT

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