INTRODUCING CHIP DESIGN USING SPEED OF LIGHT

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ABSTRACT

We present a novel didactical concept for undergraduate teaching of microelectronics based on an experiment using a CMOS cyclic pulse-shrinking time-to-digital-converter (TDC) in order to directly measure the speed of light. With emphasis on the design of a TDC for didactical purposes we use this concept in the core courses for chip design on transistor level. It starts with demonstration experiments in the physics course and in the electronic devices course in order to boost enthusiasm for microelectronics. In the context of our research on road safety we demonstrate the relevance of the field. A SPICE course and an introductory course on chip design at transistor level follow, including project-based learning, i.e. design, simulation and layout of TDC components. Within a laboratory project on electronic devices after fabrication of a chip the students are offered to characterize their own designs or to develop a microcontroller circuitry to use it. We present the integration of our concept into the syllabus of microelectronics education at the University of Applied Sciences Aschaffenburg, its operational learning objectives and the achieved learning outcomes including active learning and CDIO design-build experience. Evaluation of the courses shows that the acceptance of the didactical concept is above 90%. The speed of light experiment is ranked first by our students.

KEYWORDS

Project-based learning, chip design, TDC, speed of light, Ko-FAS

INTRODUCTION

The finite speed of light plays a fundamental role in physics and has important applications in many areas of engineering. This is observed in everyday life, e.g. using the Global Positioning System (GPS), Radio Detection and Ranging (RADAR) and laser distance meters. Nevertheless, more than 80% of our students in the first days of their academic studies do not expect that speed of light, which they know very well, can be measured on a tabletop. They never have seen any measurement before. We present this experiment in the basic physics courses of engineering education and we observe that it is denoted as a fascinating key experiment by our students. With respect to microelectronics education we have developed a novel concept in order to introduce chip design using this experiment. This concept fits into the CDIO design-implement experience and is outlined below.

The measurement of speed of light is well established in the laboratories of higher education. As modern oscilloscopes provide time resolution in the order of picoseconds, direct methods have been introduced that measure the delay of a laser pulse while travelling a short distance, e.g. [1]. By means of these experiments the student, however, up to now does not learn how the necessary time resolution is obtained electronically. For microelectronics education we instead use the inherent fascination of this experiment to introduce a simple CMOS circuitry, the cyclic pulse-shrinking TDC, in order to clarify exactly that and we explain the respective chip design. In contrast to previous experiments described in literature, where speed of light is measured, we do not place emphasis on the accuracy of measurement but on the design of the TDC.

It is widely expected that a long distance is necessary to measure the delay of a laser pulse while travelling. In a first step we use that expectation in order to raise *Attention* to the field of microelectronics by demonstrating an unexpected experiment. We show in the basic physics courses that few centimetres are sufficient using a commercial TDC and we point out that students may develop such a circuitry by presenting one of our respective dies under the microscope. At the same time we motivate our students to try the marshmallow-method [2] at home.

In the second step during the course on electronic devices we repeat the experiment with our own TDC. In the context of our research on intelligent sensors and on road safety we demonstrate the relevance and importance of the subject and we discuss the aims of our industrial research partners. By presenting a current research application of a laser distance measurement we raise *Interest* on the subject. At that stage the students are familiar with the basics of RC-circuitry and MOSFET operation. This puts us in a position to explain at an undergraduate level, how the cyclic pulse shrinking TDC works, to illustrate that by simulating the propagation delay of gates with SPICE, and to introduce, how chip layout is done. If the students feel that they got how it works, we succeed in raising the *Desire* to do it by themself. Our *Action* then is to offer a SPICE course and an introductory course on chip design at transistor level, including project-based learning, i.e. design, simulation and layout of TDC components. After fabricating a chip the students are offered the chance to characterize their own designs or to develop a microcontroller circuitry that uses the TDC in a laboratory project. The individual projects are designed to meet industry requirements.

The remainder of this paper is organized accordingly. First of all we present the syllabus and the learning objectives with respect to speed of light and time-to-digital conversion. We propose respective topics to be covered in a SPICE course, in an introductory course on chip design and via project-based learning. In a second step we describe our experimental setup for the measurement of speed of light, our didactical concept of undergraduate teaching the TDC operating principle, an example realization of a TDC for didactical purposes, respective results of measurements and a current research application of LIDAR. We present an evaluation of the concept including learning outcomes, before we summarize the main conclusions.

SYLLABUS AND LEARNING OBJECTIVES

Figure 1 shows the course flow and the higher-level objectives of our concept. Table 1 summarizes the operational learning objectives of the courses with respect to speed of light and TDCs and Table 2 presents the integration into the syllabus. Note, that at any stage of the course flow these special learning objectives fit well in the overall learning objectives of microelectronics education.

The basic tabletop experiment demonstrated in the Physics course is performed interactively, i.e. the students learn to document an experiment, evaluate the speed of light from the data

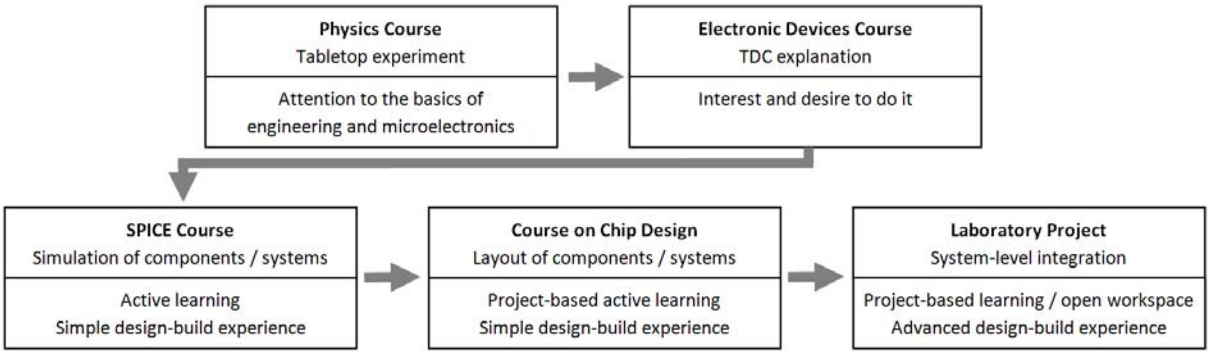

Figure 1. Course flow and higher-level objectives of our concept

Table 1
Operational Learning Objectives with Respect to Speed of Light and TDCs

Physics / Tabletop experiment	
- Explain the principle of a time-of-flight measurement - Estimate time / distance requirements for laser distance measurements by mental arithmetic - Estimate the error of measurement with respect to the definition of the speed of light	- Explain the difference between resolution, sensitivity, accuracy and evaluate these - Explain common methods for measurement of time - Explain what a TDC does - Design a time-of-flight measurement
Electronic Devices / TDC explanation	
- Show the circuit diagrams of an inverter and of a NOR gate - Calculate the switching point of an inverter using SPICE level 1 equations - Explain the sources of propagation delay of an inverter	- Calculate the propagation delay of the rising and falling edge of an inverter - Show, explain and design the circuit diagram of a pulse-shrinking TDC
SPICE / Simulation of components	
- Simulate switching points and propagation delays of CMOS inverter and NOR gates - Design an inverter with predefined propagation delays of the rising and falling edge, verify by simulation	- Design a pulse shrinking TDC and verify its correct operation by simulation - Organize in groups, partition the work and fit all together
Chip design / Layout of components	
- Layout a CMOS pulse shrinking delay line - Apply common centroid layout to minimize delay jitter	- Organize in groups, partition the work and fit all together
Lab. Project / System-level integration	
- Design a complete TDC-chip according to predefined specifications - Organize in groups, partition the work and fit all together	- Design, realize and evaluate a microcontroller circuitry for a TDC-based sensor, using a previously fabricated TDC

measured, estimate the error of measurement, discuss sources of parasitic delay and propose improvements which are realized during the lecture, if possible. By discussing engineering applications and exhibiting integrated circuits developed within our course of chip design we raise attention to the basics of engineering and microelectronics.

Table 2
Integration of our Concept into the Syllabus of Microelectronics Education

Course	Semester	Workload in total lectures	Workload of our concept in lectures
Physics 1	1	28	2
Electronic Devices	3	28	4
SPICE	4	14	1
Chip design	4	14	6
Lab. Project	6	14	14

The second experiment in the Electronic Devices course is used to introduce demonstratively simple digital CMOS circuitry, the respective propagation delay and an industrial example of use. The principle of operation of the cyclic pulse-shrinking TDC is explained on the basis of SPICE level 1 equations. By outlining how it is designed, we raise interest and desire of our students to do it.

Within the interactive SPICE course we teach simulation of microelectronic components and systems with integrated supervised exercises. These include simulation of the transfer functions of CMOS inverter- and NOR-gates, the step response of the inverter, Monte-Carlo- and worst-case-analysis of propagation delays and the application of an optimizer to determine gate width for a given propagation delay goal and predefined gate length. With respect to the TDC, the students learn to design the switching point and the propagation delay of rising and falling edges using the transient analysis of SPICE. Afterwards they are able to organize themselves in groups in order to design a simple pulse shrinking element and verify its operation with respect to an appropriate design goal. This is a first step towards active learning and CDIO design-build experience.

We use an analogue approach in the directly following course on Chip Design at transistor level. Besides elementary analog design, full custom design of basic gates for a 0.35 µm CMOS process is taught. After learning common layout skills the students handle a small personal layout project with predefined design goals. Students who like to work in a group may choose any of the matched components of a TDC as a personal task and finally build a complete TDC. They have to organize themselves in groups and to partition the work in order to achieve the design goal in appropriate time. We effectively stimulate this work by promising that all designs that pass the DRC and that meet the design goals, verified by post-layout corner simulation, will be fabricated as a multiproject chip via the EUROPRACTICE foundry service [3]. Typical project examples are a cyclic pulse shrinking delay line or a differential amplifier. This is a first step towards project-based active learning and a second step towards CDIO design-build experience.

After fabricating a chip the students are offered the chance to characterize their own designs, to implement a complete TDC or to develop a microcontroller circuitry that uses the TDC in a laboratory project. The individual projects are designed to meet industry requirements. For example, different concepts of TDC-based temperature sensors and pressure sensors have been realized and analysed in cooperation with local industry. For these projects the students are organized in groups which may either cooperate or act as competitors, just as they want to do. Each person, however, must demonstrate individual effort and creativity.

The groups are offered an open workspace, comprising the laboratories for Physics, Electronic Devices, Computer-Aided Circuit Design and Computational Intelligence, whole over the week. Finally, by a consecutive bachelor or master thesis, interested students may complete their specific knowledge and present novel ideas at a conference [4].

MEASUREMENT OF THE SPEED OF LIGHT USING A CMOS CYCLIC PULSE-SHRINKING TDC

We use the common operating principle of laser distance meters. A light pulse emitted from a laser diode is reflected by an object at distance D (two mirrors in our case) back to a photodiode at the same distance. The time of flight Δt is correlated to D according to:

$$2D = c \cdot \Delta t \tag{1}$$

where c denotes the speed of light in the medium used. If D and Δt are measured, one may confirm the value of c. As the value of c in vacuum is fixed by the definition of the metre, measurement of Δt can be used to measure D. We emphasize the measurement of Δt with appropriate resolution using a CMOS circuitry.

Experimental Setup

Figure 2 illustrates the information flow our experimental setup. Figure 3 shows the optical path. As our target audience are students of electrical engineering who learn to handle all the instruments used, there is no need to keep the apparatus simple or inexpensive. We use a high precision pulse generator in order to produce an electrical trigger-pulse of well defined duration and selectable duty cycle, typically 1 ns and 1 ms, respectively. This pulse is converted into a light pulse by a laser diode circuitry which we disassembled from a commercial laser distance meter. The light pulse is fed back via a slidable reflector (two mirrors) into a pin diode connected to a current-feedback amplifier (THS3201) in order to generate an electrical response pulse. The delay between the rising edges of the trigger pulse and the response pulse is visualized by an oscilloscope and converted into a single pulse duration via a flipflop. Our cyclic pulse shrinking TDC internally produces a number of output-pulses proportional to the duration of that single input-pulse. These pulses are counted and thus provide the digital output. For repeated measurements, the simultaneous reset pulse of the TDC and of the counter is synchronized with the laser diode pulses. Note with respect to low budgets, that high precision apparatus is not necessary for this experiment. For alternative solutions and details of FPGA-controlled pulse generation, laser diode circuitry, laser safety precautions and photodiode circuitry we refer to the literature [1], [5].

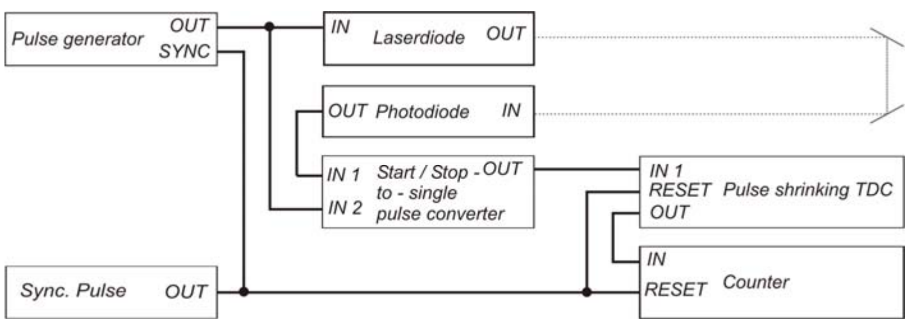

Figure 2. Block diagram of the information flow

Figure 3 shows the laser at the center, a slidable reflector at the right and the photodiode and TDC at the left. Starting the experiment at an arbitrary position of the reflector close to the laser diode results in a delay offset which is due to the time of flight but also to the contributions of the diodes and their circuitry and of the signal transmission lines to the delay. This partly is a desired effect, as our TDC requires a minimum pulse duration of about 15 ns for operation. We adjust the reflector to start with a delay of 20 ns and perform differential measurements by increasing the distance between reflector and laser diode.

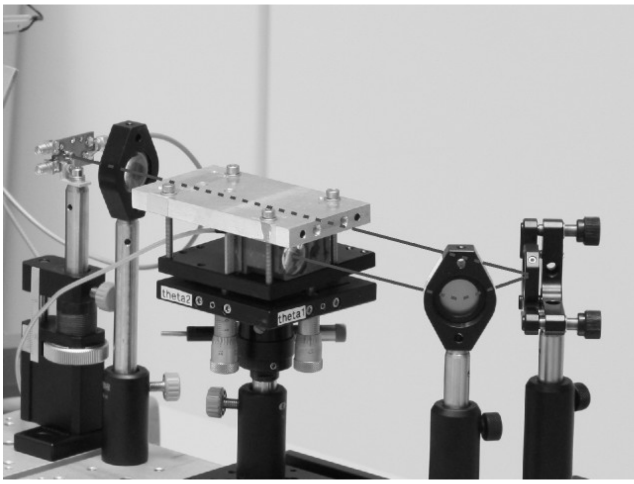

Figure 3. Optical path of the laser distance measurement on a tabletop using our TDC

The smaller the contribution of the time of flight to the offset, the more important becomes the error due to the remaining contributions induced by the displacement of the reflector. Careful alignment of the optical path is essential to ensure that the rise time of the response-impulse does not change more than some hundred picoseconds. We realized a rise time of about 2 ns and a scatter of about 200 ps within a displacement of 1.5 m.

The Pulse Shrinking TDC Operating Principle

Early realizations of a CMOS pulse shrinking TDC have been presented in [6], [7]. Its basic operation is to shrink the duration of an input pulse. To see, how that can be done, assume that we have any digital delay element that switches at 50 % of the input signal. Assume further that we can construct a propagation delay time tp_{LH} for the Low-to-High transition that is greater than the propagation delay of the High-to-Low transition tp_{HL}. If we feed a pulse into this delay element we get an asymmetric delayed pulse at the output as indicated in the upper half of Figure 4. If we feed this asymmetric pulse into a symmetric delay element, its output pulse is shorter than the original pulse.

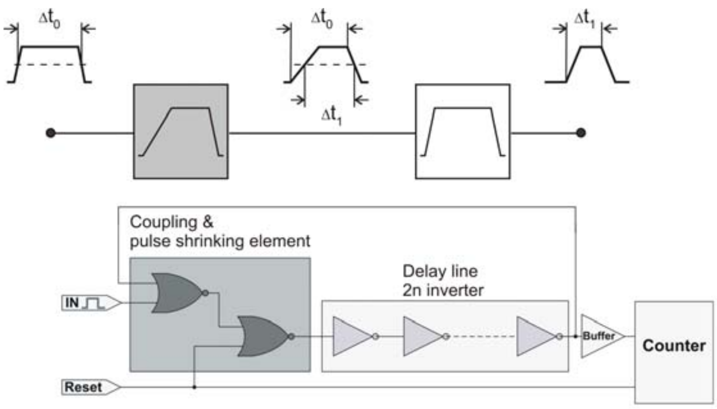

Figure 4. Pulse shrinking principle (upper half) and block diagram of the TDC

Note, that the final output pulse would be stretched, if we would construct the asymmetric delayed pulse such that $tp_{LH} < tp_{HL}$. If we connect further symmetric delay elements in series to form a delay line, the total propagation delay will increase without change of the pulse shrink. Finally, according to Figure 4 we use two NOR-gates to generate the asymmetric propagation delay, to allow reset of the delay line and to implement a feedback loop from the output of the delay line to the input of the NOR-gates. As a result the input pulse is shrinked by the same amount after each pass through the delay line until it vanishes completely. The delay line ensures that its output pulse is fed back only after the falling edge of the input pulse. Additionally, further pulses to be measured must not arrive at the input during cycling a pulse. In order to perform time-to-digital conversion, the output pulses of the delay line can just be counted using a buffer and a ripple counter. For our demonstration experiments, we show these pulses with an oscilloscope and we use an external counter.

Realization of a TDC for Education

Though any digital delay element can be used in order to build the delay line we start our educational program with the basic inverter as it is part of the ordinary courses on electronic devices, simulation with SPICE and the introductory course on chip design at transistor level. Figure 5 shows the schematics of our basic delay cell and a switch-based simple equivalent circuitry for explanation of the operating principle. For didactical reasons we have omitted temperature compensation [8] and stabilization of the supply voltage V_{DD}. As a result we are in a position to demonstrate the respective effects and our basic delay cell is kept rather simple while it operates sufficient for an appropriate measurement of speed of light.

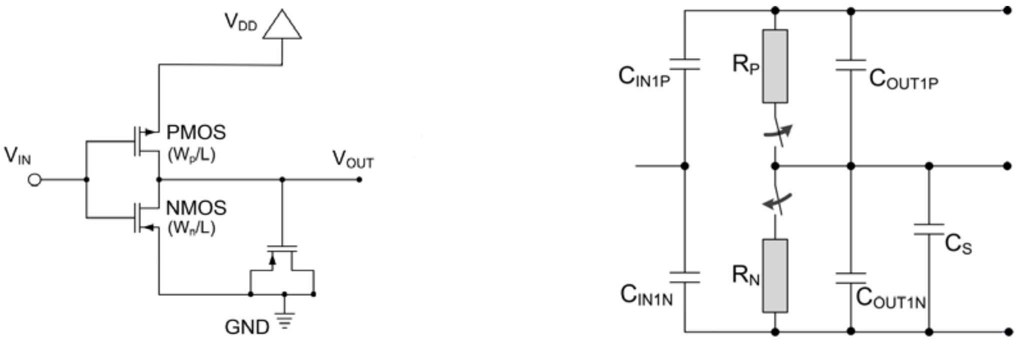

Figure 5. Schematics of our basic delay cell and a switch-based simple equivalent circuitry

At the beginning of the course on electronic devices the students are familiar with the step response of an RC circuit, so tp_{LH} and tp_{HL} are explained by a first order RC delay model, as shown at the right hand side of Figure 5. The NMOS capacitor C_S connected in parallel to the gate capacity of the following inverter is used for two reasons: at first, in order to operate the device at a frequency that allows easy access to all signals outside the chip and secondly to introduce the nonlinear C(V)-behaviour of this device. The equations which describe the propagation delay for a switching point at 50% of the amplitude

$$tp_{HL} = 0.7 \cdot RN \cdot C_{load} \quad (2)$$
$$tp_{LH} = 0.7 \cdot RP \cdot C_{load} \quad (3)$$

illustrate that an asymmetric delay element can be obtained by designing different load currents i.e. appropriate W/L ratios for the NMOS and PMOS. Generally, for two successive gates the pulse width P is reduced by ΔP

$$\Delta P = -(tp_{LH1} - tp_{HL1}) + (tp_{LH2} - tp_{HL2}) \quad (4)$$

if $\Delta P < 0$, [9]. In order to get useful equations for a hand-calculation-based design, the basic differential equation describing the charging/discharging process has to be integrated because the drain-source-voltage surpasses the saturation voltage during charging/discharging. Though the equations are easy to derive, [4], [7], this is out of the scope of our electronic devices course and usually part of a student research project. For the TDC design, however, the students have to become familiar with this approximate description and thus with the influence of mobility μ, threshold voltage V_T , supply voltage V_{DD}, capacitive load C_{load}, and gate width-to-length ratio W/L.

On our test chip we use 108 inverters within the delay line with an overall propagation delay of 290 ns (2.7 ns per inverter). As the pulse shrinking is due to propagation delay differences (see Equation 4) the cyclic pulse shrinking TDC operates with sub-propagation-delay time resolution which in first order is independent of technology parameters. We have fabricated test chips in 0.35 µm CMOS-technology [4] and we obtain a minimum pulse shrink of 120 ps. The minimum input pulse length is 15 ns. For an input pulse of 290 ns it needs about 0.8 ms until the pulse has vanished completely, the duty cycle of the input pulses must be adjusted accordingly.

Experimental Results

Figure 6 shows results which we obtain with our demonstration of laser distance measurement. The TDC has been calibrated between 27 ns and 37 ns using a high precision pulse generator (right side of Figure 6). The scatter of the time data is within 1 ns to 1.5 ns. The left side of the figure shows measured pulse counts and its reproducibility corresponding to times of flight for reflector displacements in steps of 10 cm. Every measurement has been repeated 100 times. Note, that evaluating the mean from count statistics may result in sub-count resolution which is limited, however, by the stability of the signal. Evaluating the time data at the limits, i.e. measurements 1-100 and measurements 1001-1100 corresponding to a displacement of 100 cm results in a speed of light of $2.90 \cdot 10^{10}$ cm/s, linear regression results in $2.92 \cdot 10^{10}$ cm/s. The resolution of time measurement obtained in these experiments is 260 ps, the corresponding resolution of distance measurement is about 4 cm. By an appropriate design of the TDC chip or by using a state-of-the art commercial TDC the time resolution may be reduced to about 10 ps. Due to the limited stability of the delay offset this, however, will not automatically lead to an improved accuracy of this measurement of speed of light.

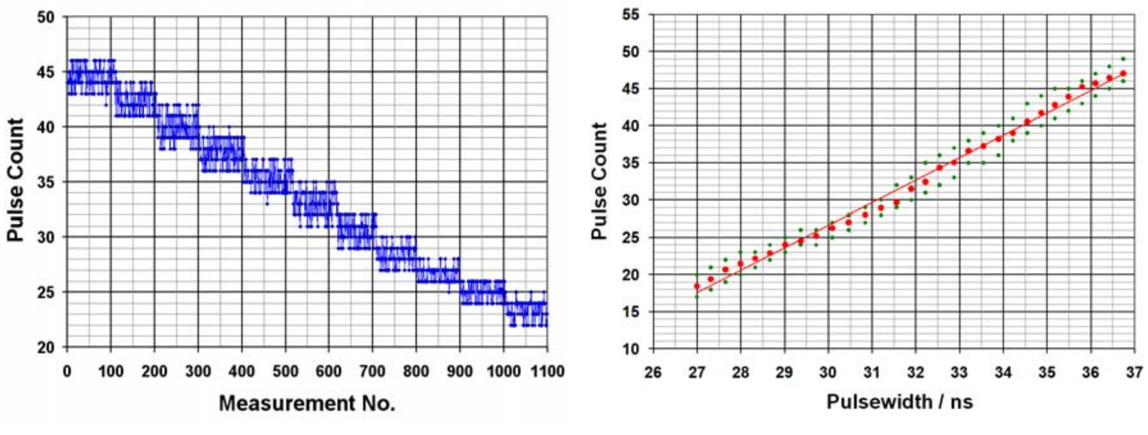

Figure 6. TDC-counts as a function of reflector displacement (left) and calibration

A Current Research Application

In order to stimulate increased interest we show our students that the technique just learned is used in the context of current research. Within the Ko-PER project of the German research intiative Ko-FAS [10], we use LIDAR-systems to detect vulnerable road users at intersections with the aim to identify critical situations, warn drivers and thus increase road safety. Figure 7 illustrates the principle. Four laser beams of a commercial laser scanner (SICK AG) scan the scene (left side). The LIDAR systems deliver angular and distance values for every reflecting object which is mapped onto a street map (right side). The clouds of reflecting points can be used to directly classify objects [11] or to generate hypotheses for video-based pattern recognition [12].

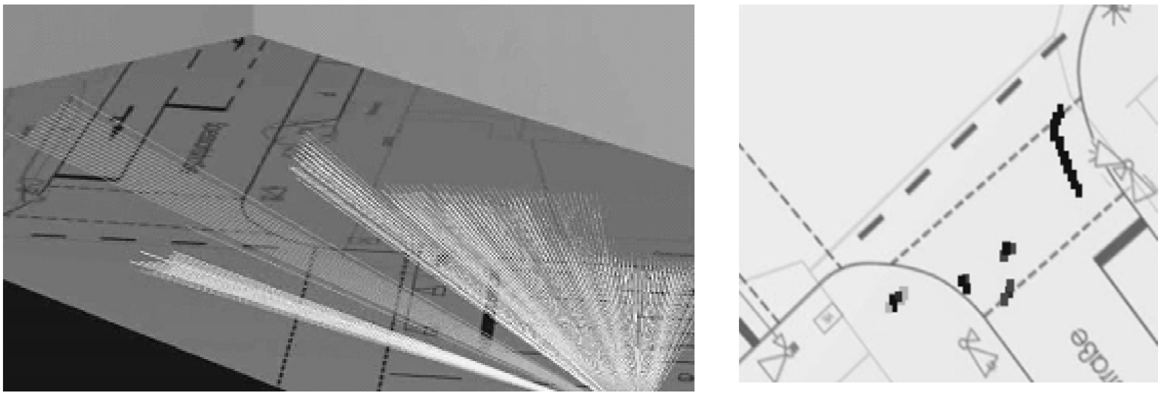

Figure 7. Current industrial research: we detect and classify road users at an intersection

LEARNING OUTCOMES AND EVALUATION

On a yearly basis all courses described above are evaluated by students. We examine the learning outcomes for every course. Table 3 summarizes the results of attained main learning outcomes of our presented concept (column 3) compared to those of the complete course (last column).

Table 3
Learning Outcomes

Course	Main intended learning outcomes of our presented concept	Attained percentage presented concept	Attained percentage overall
Physics 1	Physical design of a time-of-flight measurement including RADAR, LIDAR; Evaluation of resolution, accuracy, sensitivity	72	65
Electronic Devices	Calculation of propagation delay; TDC circuit design	80	72
SPICE	Simulation of propagation delay and TDC circuitry	91	91
Chip design	Layout of a CMOS pulse shrinking delay line	71	71
Lab. Project	Design, realize and evaluate a microcontroller circuitry for TDC or a TDC-based sensor	86	86

Within the physics course we show about 90 experiments. The speed of light experiment always is ranked under the top ten by our students. Within the electronic devices course we present about 20 demonstrations, where the TDC experiment in conjunction with a research application always ranks first. The acceptance of the concept is above 90%. This fairly well coincides with our observation, that the TDC-specific results of examination are better than the overall mean. The students are encouraged, to place comments in their evaluation. We started to introduce TDCs in our didactical concept five years ago and we never got a negative comment on it. The respective experiments are often characterized to be excellent.

SPICE, Chip Design and Laboratory Project are optional courses. Most often students that elect these courses ask for a bachelor-/master-thesis in this domain. Within our open workspace we currently supervise about 15 master students, i.e. about 20 % of the master students of the engineering faculty. 60% of them do applied research on chip or FPGA-circuit design of intelligent sensors, which shows the interest in microelectronics.

CONCLUSION

We present a novel didactical concept for undergraduate teaching of microelectronics, its learning objectives and the achieved learning outcomes. In this context we introduce an experiment using a CMOS cyclic pulse-shrinking time-to-digital-converter (TDC) in order to directly measure the speed of light. The design of the experiment and of a TDC for educational purposes is described in detail. The atmosphere during the lectures, the questions of the students and the evaluation of the courses show that the measurement of the speed of light on the tabletop together with the explanation, how the electronics work, with the perspective to design a respective chip and with the demonstration of a current research application which may safe human life fascinates our students. Partly we refer this fascination to the fact that we present a measurement of a basic physics quantity, which is far beyond the acquisition capability of the human sense organs. We also observe a similar effect when we present scanning tunneling microscopy on the tabletop, however in the students' opinion, the speed of light measurement using the TDC ranks better.

The students' evaluation of the courses shows that the acceptance is above 90% and the TDC-specific results of examination are better than the overall mean. We observe strong interest in a bachelor-/master-thesis in this area of work. Based on these data we conclude that we succeeded in boosting students' enthusiasm for the field of microelectronics within our engineering faculty.

ACKNOWLEDGEMENTS

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Ulrich Brunsmann is a Professor in Electronic Devices and Computational Intelligence. As Founding Dean of the University of Applied Sciences Aschaffenburg he was responsible for curriculum development of the faculties Engineering and Business Administration and Law in cooperation with the *Bayerisches Staatsministerium für Wissenschaft, Forschung und Kunst*.

Ulrich Brunsmann and Konrad Doll promote the integration of industrial research and project-based learning into the undergraduate teaching program. They share the research interest in Intelligent Sensors and Advanced Driver Assistance Systems. Several of their master students received an IEEE Best Student Paper Award.

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