International Journal of Engineering Education Vol. 34, No. 4, pp. 1411–1426, 2018
Printed in Great Britain

0949-149X/91 $3.00+0.00

Multifunctional Radar Sensor Laboratory Course Using a Low-Cost Software-Defined Radio Transceiver*

SE-YEON JEON, KONSTANTIN NIKITIN, AULIA DEWANTARI, SUMIN KIM and MIN-HO KA*
School of Integrated Technology, Yonsei Institute of Convergence Technology, Yonsei University, 85 Songdogwahak-ro, Yeonsu-gu, 21983, Incheon, Republic of Korea. E-mail: kaminho@yonsei.ac.kr

This paper presents a radar laboratory course and an educational radar kit developed for the course. This course aims to provide hands-on experience on pulse-Doppler radar (PDR) signal processing algorithms using modern methods and tools. Experiments and project-based learning (PBL) is introduced to the pedagogical methodology of this course. The course is constructed by considering various backgrounds and levels of the students. The student learning consists of three elements: theoretical knowledge, experiments, and proposal writing on their own research topic. The objective of convergence education is reflected on how the students are provided the opportunity to apply their knowledge and expertise in radar system obtained through this course to their own research areas. For an efficient application of the PBL, a suitable educational kit is designed and implemented. The kit is developed as an open software and hardware platform for facilitating the experimental studies of modern radar technologies for students. The kit, a low-cost multifunctional short-range PDR, is a relatively simple platform for beginners. The suggested hardware design is based on a single-chip software-defined radio (SDR) with an inexpensive system-on-chip (SoC). As the experimental prototype is based on commercially available evaluation modules, it is easy to assemble and use, and no special skills or equipment are required. The proposed system enables students to study modern signal processing techniques. The applied pedagogical methodology, course description, experimental kit, projects descriptions, and assessments are discussed.

Keywords: education; hands-on experience; laboratory; project-based learning; radar; pulse-Doppler radar; software-defined radio; experimental kit

1. Introduction

With respect to the current methods of instruction in modern radar theories and techniques, there exists a pressing need for a practical approach to the material. To provide practical research skills to students, engineering education should integrate theory and practice, link hardware development and software implementation, and expose students to practical issues and real-world problems. In this sense, laboratories and experiments are widely used as engineering education methods. In addition, the development of appropriate modules and equipment is essential for achieving educational objectives. These attempts has been made throughout the wide range of engineering disciplines: computer science [1, 2], robotics [3], agricultural engineering [4], and chemical engineering [5]. In the field of radar engineering, experiments and their visualized results can significantly motivate students, increase their knowledge of the theories, and expose them to modern radar applications. Hence, several laboratory courses related to the radar have been offered [6–9], and radar modules for instruction have been developed for similar courses [10–12].

Radar technology classes and labs are attended by students with different backgrounds and various research interests. Some of them expect to study microwave theory and technology, while the others are interested in embedded and real-time signal processing, tracking, or in other topics. The objective of practical lessons is not only to encourage students to complete their research but also to assist them in acquiring cooperative skills. As a typical semester course is limited to approximately three months or to twelve lessons, it is important to minimize non-essential work and choose an effective pedagogical method.

Recently, project-based learning (PBL) has been emerged as an efficient pedagogical strategy. The applications and effectiveness of PBL in engineering education are discussed in [13–18]. PBL enables learner-centered education, active learning, as well as inter- and multi-disciplinary education. PBL is also introduced to stimulate student engagement and creative thinking. There have been attempts to apply the PBL in lectures and laboratory courses in various engineering areas such as embedded systems [13], mechanical engineering [14, 15], mechatronics [16], communication systems [17], signal processing [18].

Integrating diverse disciplines in education and research is a fundamental goal of the school in which this course is held. Since the school pursue convergence education and the students have different specializations, building courses for the graduate students could be challenging. Both the materials and the teaching method should be care-

---

* Accepted 14 March 2018.

fully considered when constructing a course, so that the course contents can be well-understood by students from different backgrounds.

A one-semester radar laboratory course is proposed, wherein, students can practice experiment procedures, device connections, acquire real data, perform signal processing, and display the results. This course is constructed based on two main consideration, which are appropriate pedagogical strategy and proper educational kit. The description of the pedagogical method and the development of the radar kit are discussed in detail throughout the paper. Experiments using the kit, and PBL has been adopted as the pedagogical methodology for the radar laboratory course to enhance student learning via hands-on experience. The course includes important components of a radar course: theoretical lectures and software and hardware practices. This course includes three laboratory experiments. An educational radar system that can be used for these experiments has been developed. Providing radar education to students in different backgrounds and helping them in their research fields as much as possible was the main issue of this course. To achieve it, one aspect of PBL was brought to this course. The students themselves questioned and searched the research topics using the radar kit in conjunction of their research fields and radar technology and submitted it as a research project proposal.

The significance of this course is that it is constructed by considering the various backgrounds and levels of the students, in accordance with the educational objective of the school. Since the interests and purposes of the students may vary due to their diverse research fields, the conventional teaching method might not be an effective choice for the course delivery. Therefore, this course adopts a new method where the students are given the opportunity to have a more flexible and personalized learning experience. This can be done by taking advantage of software-defined radio (SDR) radar kit with various functions that is especially designed and implemented for this course.

The proposed course is for senior undergraduate and graduate students of electrical and electronics engineering, computer engineering, information technology, and radio and microwave engineering. As a prerequisite for the course, students are suggested to have a basic understanding of the radar fundamentals.

2. Background

The School of Integrated Technology (SIT) of Yonsei University in Korea is the 8th and the newest school under the college of engineering, which was first established in 2011. It was selected for the 'ICT Consilience Creative Program', which is supported by the Korean government's Ministry of Science and ICT (MIST). The fundamental goal of this school is to integrate diverse

disciplines into its education and research. This goal is reflected in both its undergraduate and graduate curriculum. Based on the curriculum structure of SIT, the undergraduate students are given several basic courses in various fields of study during their first year of enrollment. During the second and third year, they have the opportunity to focus their study into the field of their choices, based on their preferences and their first year experience. The graduate school consists of four research groups: Computation & Communication, Seamless Transportation, Medical Systems, and Smart Living. Each research group is subdivided into more specialized laboratories. The students can join one of the four research groups that best fits their interest. Accordingly, they are required to take courses related to their field of study. In addition, they also need to take at least five courses outside of their field of study as a graduation requirement. The majority of the undergraduate students of SIT continue their study and become students in the graduate school. Since they have different specializations due to the undergraduate curriculum structure, building courses for the graduate students could be challenging. Both the materials and the teaching method should be adjusted to make sure that the course contents can be well-understood by students from different backgrounds. The frequently occurred circumstance in the undergraduate and graduate courses in SIT over the years is the students' score distribution concentrated on both ends without showing a typical bell curve. For the students who are familiar to the subject of a course, the course contents are not challenging or advanced enough, and for those who are not, it is very difficult to follow the course. Years of experience have shown that there is a limit to the content-based learning approach in mitigating this tendency. The proposed course tried to handle such circumstance through hands-on experience and project-based learning.

3. Objectives of the laboratory course

The objective of the radar laboratory course (CO) is to instruct and assist students in achieving the following:

- CO1: System level insights into modern radar technologies.
- CO2: Knowledge in radar theories and signal processing algorithms.

- CO3: Skills related to experimental procedures and device handling.
- CO4: Hands-on experiences of radar hardware and software.
- CO5: Opportunity to exercise result visualization and analysis with real data.
- CO6: Chance to integrate radar technology into multiple disciplines.
- CO7: Increased interest and motivation in radar technology.

The syllabus of the course, including the schedule and topics, is described in Table 1. The course includes the study of electromagnetic wave propagation, antenna design, transceiver circuits, embedded systems, and signal processing algorithms. Students can obtain system level insights into modern radar technologies. They can design, fabricate, and test the antennas using the educational radar. Students can also practice field-programmable gate array (FPGA) and embedded processor programing for controlling the transceiver, save the data, and display the results. Further, they can study advanced signal processing algorithms and apply them to the acquired data. To provide students with a project-based hands-on experience in radar technology, the proposed course includes three laboratory projects:

- Range performance estimation.
- Monopulse radar test.
- Polarimetric radar experiment.

With respect to the course objective, student learning outcomes (LO) are derived as follows:

- LO1: Describe modern radar system composition and subsystems.
- LO2: Perform basic radar signal processing algorithms.
- LO3: Explain various functions of the radar and process/analyze/visualize real radar signal.
- LO4: Setup and execute experiments properly.
- LO5: Discuss the process of radar research projects and write a research project proposal.
- LO6: Perform functions in a team.
- LO7: Write reports and make presentations clearly and efficiently.

The factors which influence the design of the course and experiments are as follows:

- Contents: Course objective and learning outcomes.
- Student background: Wide spectrum of student backgrounds (electrical and electronics engineering, computer science, materials engineering, etc.).
- Class size: Number of students and instructors who can technically aid the students.

Table 1. Radar laboratory course syllabus

Week	**Topic**	**Contents**	**Course objectives**	**Learning outcomes**
1	Introduction	Overview of the course: Objectives of the course, schedule and contents		
Part 1: Radar System				
2	Modern trends in radar systems	Functions, block diagrams, and modern trends	CO1	LO1
3	Subsystem 1: Antenna	Electromagnetic wave propagation, antenna design, EM simulation tools		
4	Subsystem 2: Transceiver	Block diagrams, circuits, ADC		
5	Subsystem 3: Embedded system	FPGA, processor, Xilinx Tool		
6	Subsystem 4: Host software	C, MATLAB		
Part 2: Laboratory Projects				
7	Signal processing techniques	FMCW, matched filter, pulse compression, object detection, CFAR	CO2	LO2
8	Experiment 1: Range performance estimation	Radar range equation, range-Doppler, object detection	CO3 CO4 CO5	LO3 LO4 LO6
9	Experiment 2: Monopulse radar test	Phase-comparison methods, Azimuth estimation		
10	Experiment 3: Polarimetric radar experiment	Polarimetric scattering coefficients		
11	Research project proposal (1)	Write/edit/execute a project proposal	CO6 CO7 CO1	LO5
12	Research project proposal (2)	Write/edit/execute a project proposal		
13	Research project proposal (3)	Write/edit/execute a project proposal		
14	Presentation and report	Present the final version of project proposal and the results		LO7

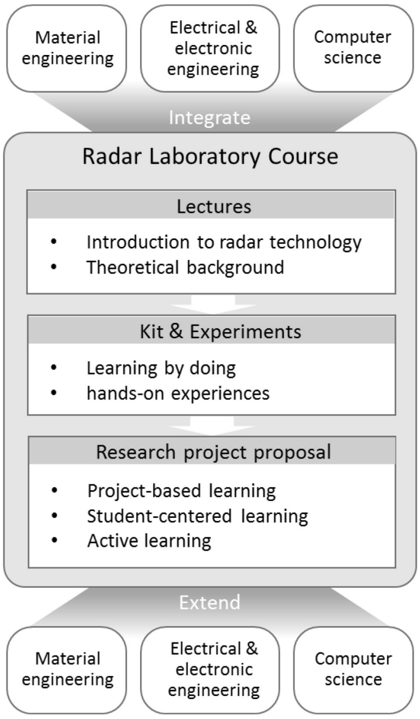


Fig. 1. Diagram of course configuration and the function of each component.

- Resources: Specification and flexibility of the educational radar kit (frequency range of the radar, number of transmit/receive channels, etc).

The pedagogic aim is to educate students with different backgrounds and various research interests on modern radar systems. In this course, the learning process consists of several stages as shown in Fig. 1. In the first stage, the students are given the theoretical knowledge of radar system. In the next stage, the students are given the chance to further understand how radar works by doing hands-on experiments with the radar kit. Finally, the students are also given a task to design a research topic that can be realized using the provided radar kit. From this research topic, students are required to write a proposal that will be presented and then revised based on the feedback from the professor and the other students. This proposal writing provides the opportunity to learn radar system requirements as well as the process of radar research projects.

Students use the kit to receive radar signals and practice signal processing, using MATLAB (or C, Scilab, R, etc.), in this course. During the experiments, students can observe the real-time visualization of the received signals and the processed signals as depicted in Fig. 2. This increases student motivation and enables the students to better understand the information contained in the received radar signal and the goal of signal processing. Additionally, they can develop the ability to handle equipment and conduct experiments. Through these experiments, students can study the operating principles of modern radar systems and integrate the theoretical and practical issues of radar technology.

The flexibility of the educational kit enables learner-centered education, which is an advantage of the PBL, as follows:

- Depending on the students' purpose, needs, and abilities, the developed kit can provide experience in implementing and testing the subsystems of the

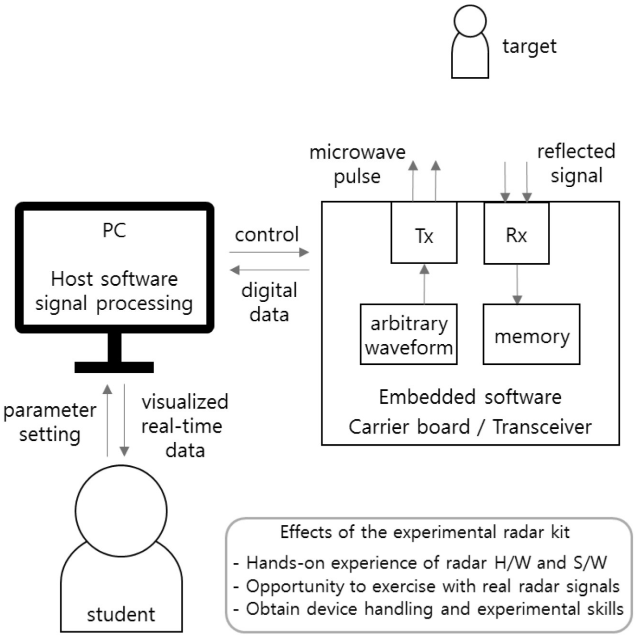


Fig. 2. Diagram of students using the kit during the course.

kit. For example, students interested in embedded systems can directly implement radar functions through FPGA programming; they can test the results by replacing the provided kit with their own implementation. Students interested in GUI programming can implement the software that processes the received radar signal and plot it in real time. Those interested in signal processing algorithms can implement and apply advanced detection algorithms, whereas those interested in antennas can design and fabricate antennas, according to the radar frequency range and test the performance using the supplied radar kits.

- Due to the flexibility of the SDR system that can implement various functions, students can use the kit to perform more advanced experiments such as the SAR or the MIMO radar and can design and suggest experiments using the kit.
- From beginners to skilled engineers, appropriate education can be provided to all based on their abilities.

4. System configuration of the experimental radar

4.1 Design of the experimental radar

The development of a suitable educational radar for laboratory projects is necessary. Currently, the most common approach for radar laboratory education is the usage of a homodyne transceiver [6, 8, 16]. As a rule, these sensors use one of the various types of linear frequency-modulated signals and include relatively simple signal processing based on embedded microprocessors. Such sensors are used in various areas including vehicle safety systems [19], object detection [20], synthetic aperture radars (SAR) [21, 22] and imaging [23]. Besides, industrial and self-made homodyne sensors are widely found in universities as educational and demo aids. The advantages of these transceivers include easy implementation, low costs, and a safe output power. Nonetheless, the homodyne sensor is not suitable for educational purposes owing to the following reasons: First, the type and modulation parameters of the transmitted signal are fixed. Further, the sensitivity of the receiver is limited by spurs caused by transmitted signals in the background.

Based on our experience and as per the current demands, the following basic requirements were considered in the choices made in the design of the educational radar kit:

- The transmitter should be capable of outputting a coherent sequence of microwave pulses with customizable or arbitrary shapes and modulations.
- The receiver must be capable of converting the input signal into a form suitable for future digital signal processing at an intermediate frequency.
- The signal processing should provide various means for real-time data transfer and processing.
- The parameters of the educational radar should be accessible and variable.
- The setup must be safe and reasonably less prone to possible abuse.

The modern trend in microwave transceiver development is to use an SDR and a FPGA for flexibility in implementation. An FPGA is used in SAR systems [24], and human sensing radar applications [25]. The flexibility of the SDR systems is discussed in [26]. SDRs are also used for target detection in automotive applications [27], high

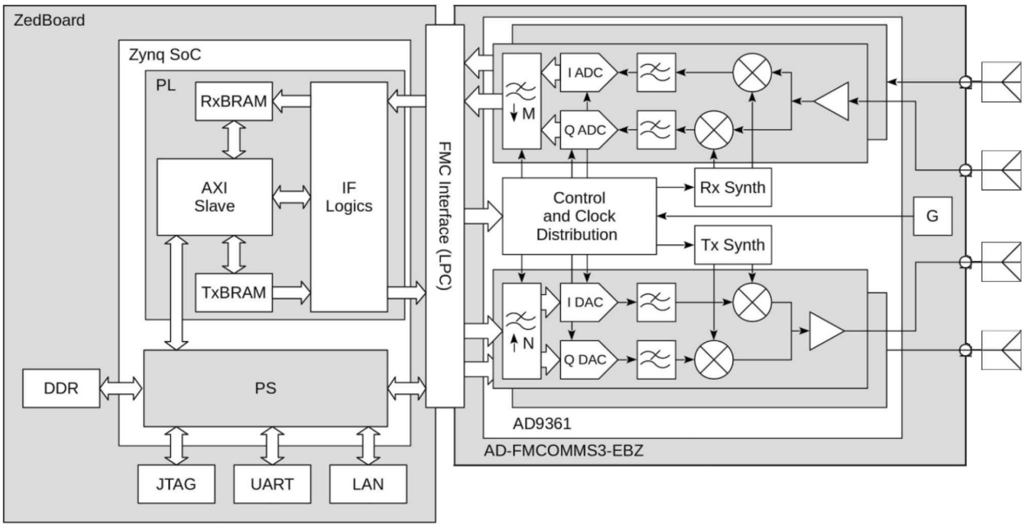


Fig. 3. Block diagram of the experimental radar using AD9361 as a transceiver and ZedBoard as a carrier board.

resolution target detection [28], radar imaging systems [29], and human motion sensing radars [30].

For the development of an experimental transceiver design comparable to the cost of popular sensors and for providing extensive possibilities for learning and research, it was found that the discussed requirements were satisfied by one of the SDR transceivers widely used in wireless communication. The proposed hardware includes a single-chip SDR transceiver, an FPGA accompanied by a dual-core embedded processor, memory, and a gigabit local-area network (LAN). A radar kit that can be modified to suit diverse objectives with single platform will be very helpful to use in radar education.

4.2 *Hardware structure*

The block diagram of the proposed experimental radar is shown in Fig. 3. It consists of a transceiver, a carrier board, embedded software, and host software. Various wideband antennas [31, 32] and suitable cables for a frequency range of 2–6 GHz have been used. A host computer is used for both software development and analysis of the experimental results. It is connected to a ZedBoard by LAN. Serial and JTAG interfaces are used for embedded software testing. The implemented educational kit is shown in Fig. 4.

Figure 5 shows the transceiver and the carrier board.

4.3 *Transceiver*

The radar transceiver is based on the AD-FMCOMMS3- EBZ [33] evaluation board for the AD9361 [34] single-chip dual-channel SDR transceiver. AD9361 is a high performance, highly integrated radio frequency Agile Transceiver^{TM} manufactured by Analog Devices Inc. These integrated circuits contain an almost complete digital transceiver including quadrature DACs and ADCs, baseband filters, and a direct conversion transmitter and receiver. The AD9361 contains two transmitter paths and two receiver paths. The evaluation board contains all the necessary parts for a transceiver including secondary voltage converters, a clock reference, impedance matching, and input/output microwave connectors. This board is designed as an FPGA mezzanine card (FMC) and meets most of the VITA-57.1 [35] specifications. The evaluation board is developed to operate within the full frequency range of the AD9361 transceiver, from 70 MHz–6 GHz.

4.4 *Carrier board*

The ZedBoard [36] development kit for the Xilinx Zynq-7000 [37] SoC is an inexpensive FMC carrier board supported by the AD-FMCOMMS3-EBZ kit. It features the XC7Z020-CLG484 all-programmable SoC with a 512 MB DDR3 SDRAM, a gigabit Ethernet LAN port, and a low-pin-count (LPC) FMC interface.

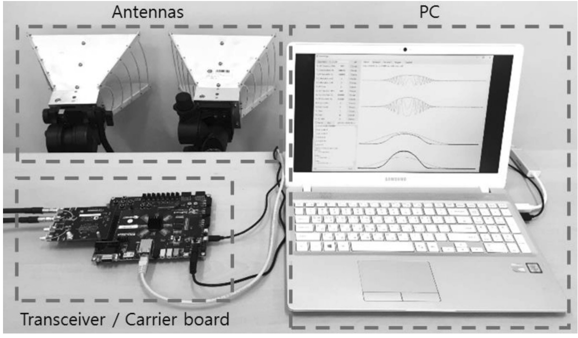


Fig. 4. Implemented educational radar including the transceiver, the carrier board, PC, and antennas.

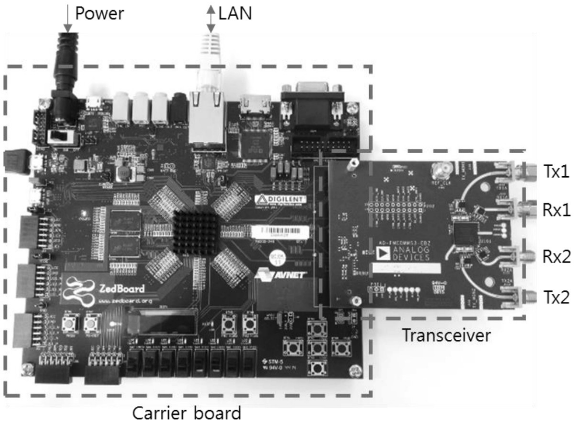
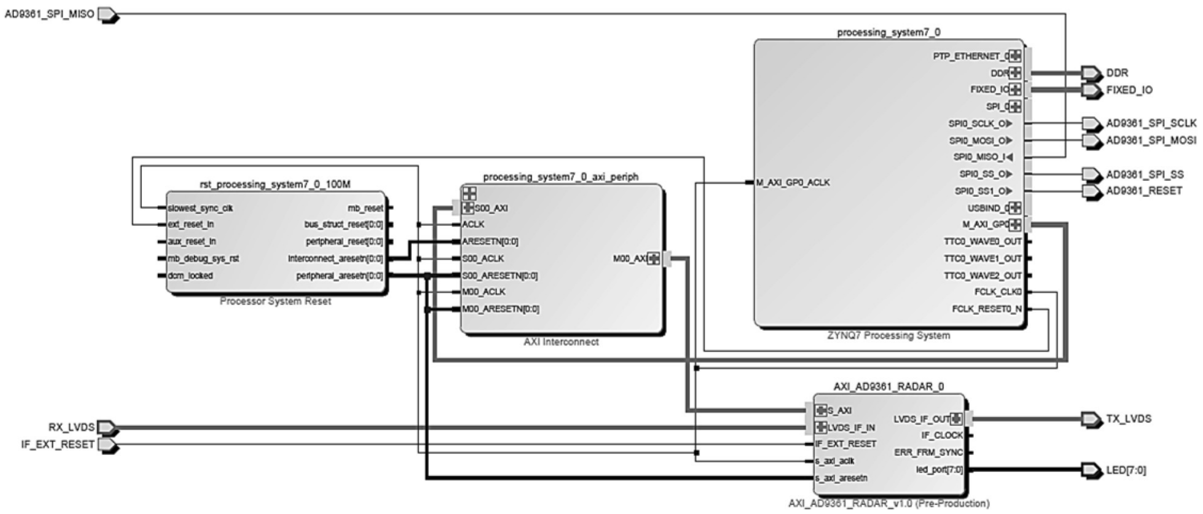
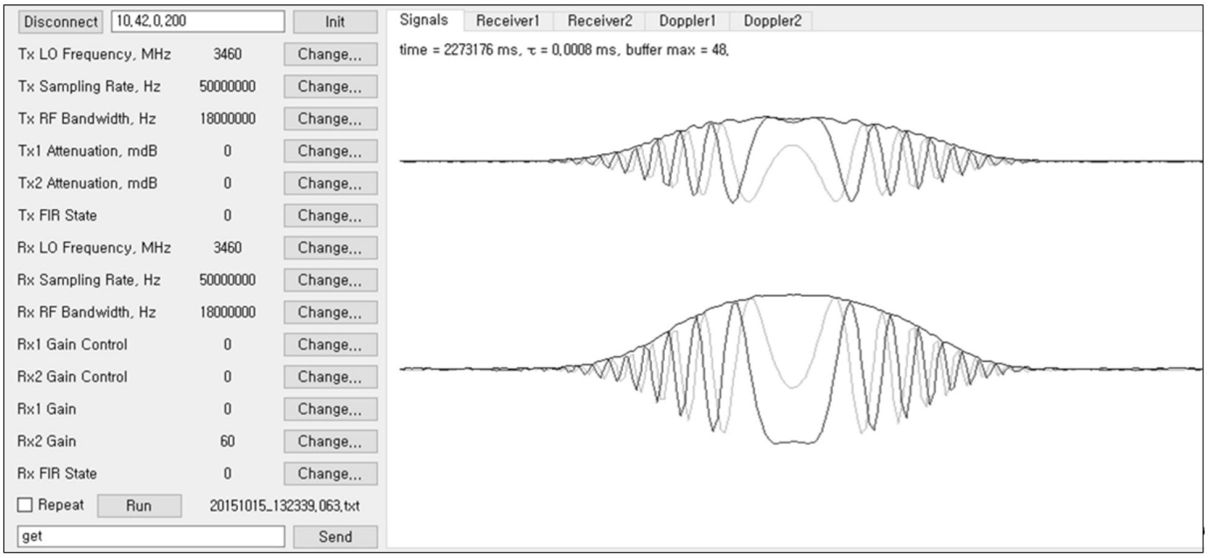


Fig. 5. The transceiver and the carrier board.

The AD9361 RX signal path passes the down-converted signals (I and Q) to the baseband receiver section. The baseband RX signal path is composed of a two-stage programmable analog low-pass filter, a 12-bit ADC, and a four-stage digital decimating filter. The AD9361 TX signal path receives the 12-bit data in the I-Q format from the AD9361 digital interface, and each channel (I and Q) passes this data through a four-stage digital interpolating filter to a 12-bit DAC. The DAC's analog output is passed through a two-stage low pass filter before the RF mixer. The four blocks leading to the DAC comprise the digital filtering for the transmitter path. These programmable filters provide bandwidth limiting that is required prior to conversion from digital to analog. They also provide interpolation for translating the input data rate to the rate needed for an adequate digital to analog conversion. In each filter, the interpolation is performed first, followed by the filter transfer function.



(a)



10.42.0.200

Tx LO Frequency, MHz 3460
Tx Sampling Rate, Hz 50000000
Tx RF Bandwidth, Hz 18000000
Tx1 Attenuation, mdB 0
Tx2 Attenuation, mdB 0
Tx FIR State 0
Rx LO Frequency, MHz 3460
Rx Sampling Rate, Hz 50000000
Rx RF Bandwidth, Hz 18000000
Rx1 Gain Control 0
Rx2 Gain Control 0
Rx1 Gain 0
Rx2 Gain 60
Rx FIR State 0
☐ Repeat 20151015_132339.063.txt
get

time = 2273176 ms, τ = 0.0008 ms, buffer max = 48.

(b)

Fig. 6. (a) The embedded software development with Verilog, and (b) the host software development with C.

4.5 Embedded software

The radar evaluation software consists of an FPGA configuration, a program for the embedded processor, and a data analysis program for the host computer. The main objective of the evaluation software is to provide a framework for data transfer from the receiver to the FPGA, from the FPGA to the embedded processor, and from the embedded processor to the host computer. This structure allows students to start software development using high-level programming tools on the host computer and later re-implement the well-tested algorithms on the FPGA or on the embedded processor. The software is organized in compact modules and permits parallel and significant modifications. The control logic is clocked synchronously with the transceiver from the same frequency of 240 MHz provided by the multiplication of the ADC data output period of 60 MHz by 8. The pulse repetition frequency is 640 Hz, obtained by the division of the major clock by 375,000. Fig. 6(a) shows an example of embedded software development.

4.6 Host software

The received signals are stored in the host computer in a simple text format. Although the experimental results shown in this paper are processed in MATLAB [38], students may choose alternative tools (e.g., Scilab, R, or others) for digital signal processing, based on their preferences and study objectives. This approach enables the design, study, and the debugging of the algorithms using real radar signals and high-level design tools. Students may also implement their algorithms on the FPGA or on the embedded processor for obtaining real-time performances. Fig. 6(b) shows an example of host software development.

5. Laboratory projects

The students in this course are scheduled to carry out three experiments. The experiments were provided to the students to achieve CO3-5 which correspond to LO3, 4, and 6. As shown in Fig. 1, the experiments are the link between radar theory and proposal writing. The main function of the experiments in this course is to strengthen the students' knowledge of radar theory by deviating from the textbook level, and to let the students learn about the operation of the radar kit, the functions of each part of the kit, and the flexibility of the kit so that the students can write the project proposals.

From the experiment 1 to 3, one transmit or receive channel is added. In experiment 1, a transmit channel and a receive channel were used to detect the range and velocity of the target through basic radar signal processing. In experiment 2, one receive channel is added, so that the azimuth angle of the object can be calculated from the phase information of the signals received in both receive channels. In experiment 3, a transmit channel is added, so that the students can learn the polarimetric diversity can be provided to the transmit channels, and the orthogonality between the transmit channels is required. By gradually increasing the number of channels, students can learn basic radar theory and signal processing first and study the diversity of signal processing and target information obtained by adding channels. Students can learn how to handle equipment while performing experiments. They can also change the parameters of the radar and the target during the experiment and check the real-time data to visually confirm the radar theory. The theories to be studied by the students and the outdoor experimental results of each project using the kit are shown in this section, as examples of the possible outcomes of the laboratory projects.

To help students with various backgrounds in their research fields, PBL was introduces to this course in the form of project proposal writing. The students searched the research topics that integrates their research fields and radar technology and submitted it as a research project proposal.

5.1 Pulse compression

(1) Objective and principle: In this topic, students become familiar with the raw data formats of the received radar signal and practice signal processing using software such as MATLAB. A typical pulse compression algorithm [39] is implemented. The matched filter output is calculated as

$$y = S^{RX} \otimes h, \tag{1}$$

where S^{RX} is the received signal and h is the impulse response of the matched filter.

$$h_i = ({S^{TX}}_{I-i})^* \tag{2}$$

is obtained as the complex conjugate of the flipped probe signal, S^{TX}, where I is the number of range elements.

To reduce the computational load, the actual compressed data are obtained as follows.

$$y = IFFT(FFT(S^{RX}) \cdot H), \ H = FFT(h). \tag{3}$$

Doppler processing is applied to determine the radial velocity of the object. The Doppler frequency is obtained by performing a Fourier transform along the slow-time axis.

(2) Assignment: Students are provided with the raw data of the received radar signal, using the kit. They perform pulse compression. They plot the transmitted, received, and the pulse-compressed signals, and compare them to understand the principles of pulse compression. They apply CFAR algorithms to the pulse-compressed signal to detect the object.

5.2 Experiment 1: Range performance estimation

(1) Objective and principle: The main goal of this experiment is to learn range-Doppler processing and radar range equation, and to estimate the radar performance in detecting walking pedestrians. According to the radar equation [40], the maximum detection range of an object with a radar cross section of σ = 0.5 m^2 is determined as:

$$R_{MAX} = \sqrt[4]{\frac{P_{TX} G_{TX} G_{RX} \lambda^2 \sigma G_{PC}}{(4\pi)^3 P_N D \cdot L}} \tag{4}$$

where P_{TX} is the transmitter output power; G_{TX} and G_{RX} are the gains of the transmitting and receiving antennas, respectively; λ is the wavelength; D = 15 dB is the signal-to-noise ratio required for reliable object detection; and L is the loss factor. $P_N = kT_n\Delta_f$ is the receiver noise determined by the noise temperature, T_n, and a bandwidth, Δ_f = 57 MHz; $k \approx 1.38 \cdot 10^{-23} JK^{-1}$ is the Boltzmann constant. The last parameter $G_{PC} \approx 48$ dB represents the pulse compression gain. For λ = 10 cm, P_{TX} = 2 mW, G_{TX} = 10 dB [31], G_{RX} = 10 dB [32], T_n = 600 K, and an estimated loss factor, L = 16 dB, the maximum detection range is expected to be approximately, R_{MAX} = 120 m.

(2) Experiment: The experiment is performed on a moving object (walking pedestrian). The students may play the role of the object by approaching or moving away from the radar. Using the educational radar kit, they can observe the moving objects in the range-Doppler plane in real time, during the experiment. This enables students to learn the concept of the range-Doppler plane. Students can vary the center frequency of the kit to observe the changes in the range performance.

(3) Assignment: Students perform range-Doppler processing on the raw data obtained during the experiment. They plot the result in various forms (2D or 3D) to practice effective data visualization as shown in Fig. 7. They compute the distance and velocity of the detected object. For example, the detected object at 120 m range is shown in Fig. 7(c), and the estimated velocity is 1.29 m/s. They then compare the radar range equation results with the range performance results through experiments and report the differences, according to the frequency variation of the radar kit.

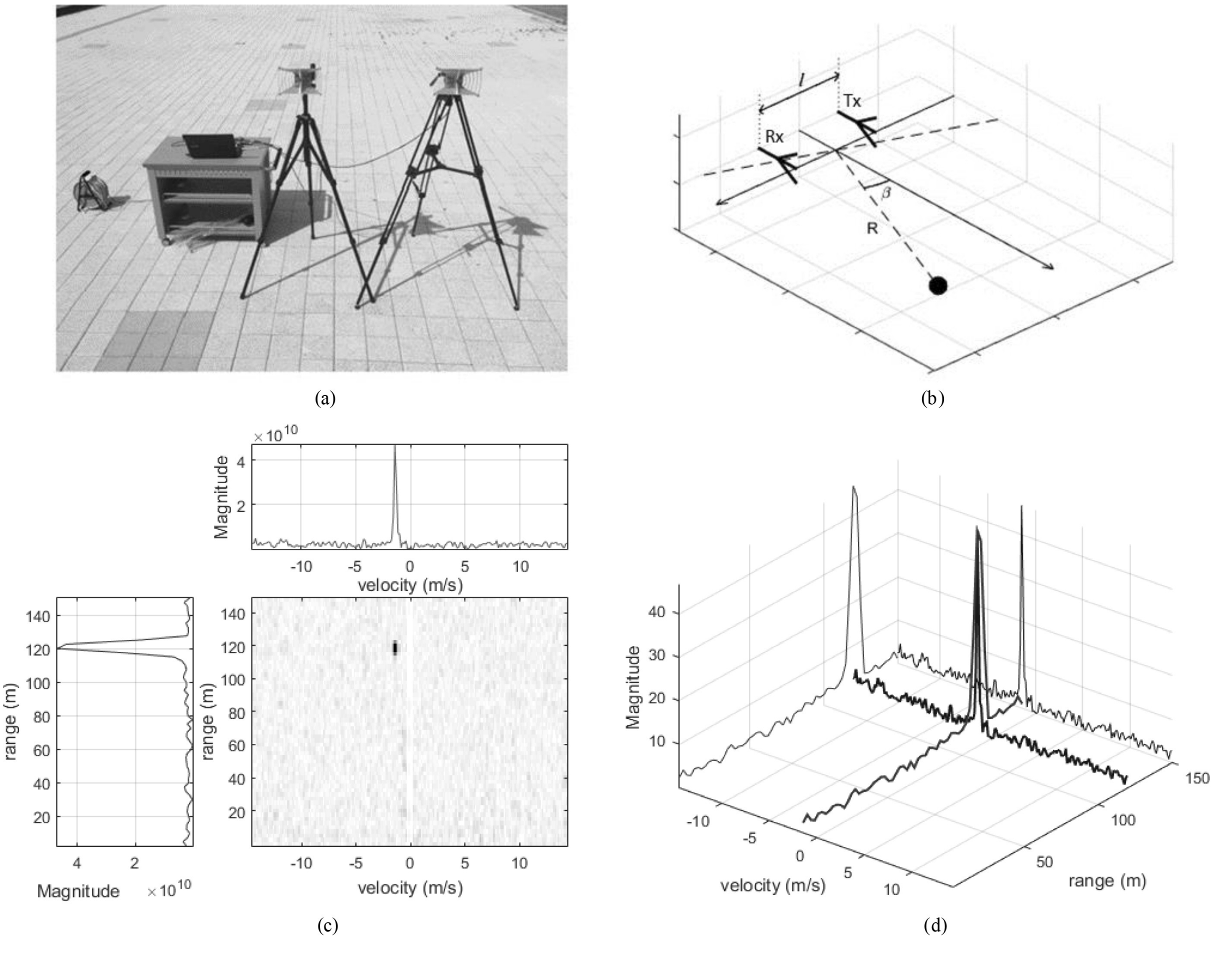
5.3 Experiment 2: Monopulse radar test

(1) Objective and principle: The purpose of the experiment is to learn the principle of the phase-comparison monopulse technique and estimate the azimuth of the detected object. Assuming that a single transmitting antenna and two receiving antennas are connected to the transceiver, the azimuth of the detected object can be estimated. The difference in the phases of the signals received by the two antennas is determined by the distance between the receiving antennas, l, the azimuth of the object, β, and the wavelength, λ, as shown in Fig. 8 (a). As a result, the azimuth estimation based on the measured phase difference is:

$$\beta = \sin^{-1}\left(\frac{\lambda\Delta_{\phi}}{2\pi l}\right) \tag{5}$$

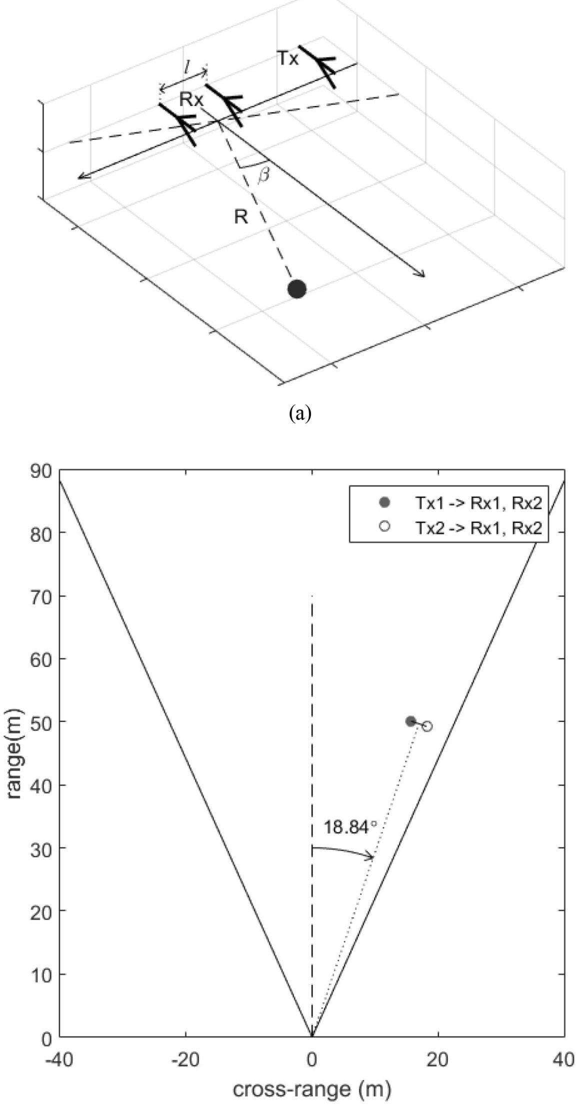
(2) Experiment: The experiment is performed on a moving object (walking pedestrian). Students may play the role of the moving object. Using the educational radar kit, they can observe the range and azimuth of the moving objects in real-time.

(3) Assignment: Students apply the phase-com-



(a) (b) (c) (d)

Fig. 7. Range performance testing: (a) photograph of the outdoor experiment, (b) geometry of the experiment, and (c) 2-D plot of the range-Doppler result, (d) 3-D plot of the range-Doppler result.



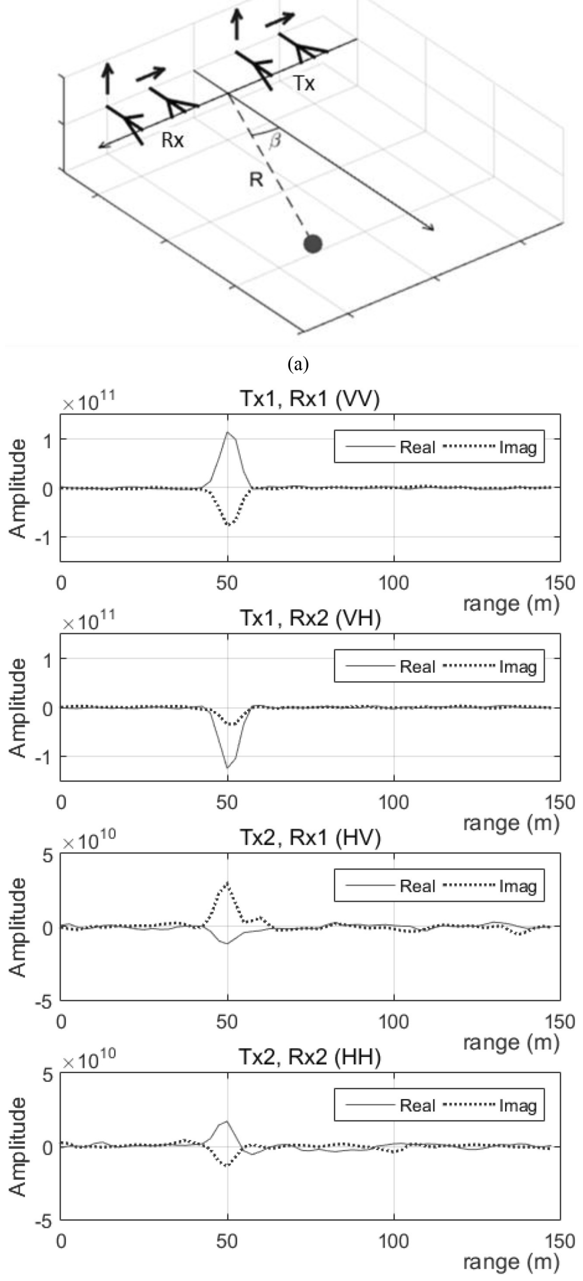
(a)

(b)

Fig. 8. Monopulse azimuth measurement technique: (a) scheme of the experiment, (b) estimated azimuth.

parison monopulse technique on the detected objects to estimate the azimuth of the object. They plot the location of the detected object accurately, according to the range and azimuth of the object. It helps students to practice plotting in the polar coordinates. Students can plot the range and azimuth of the detected object in the spatial domain as shown in Fig. 8 (b). The range and azimuth of the plotted object are 50 m and 18.84°, respectively.

5.4 Experiment 3: Polarimetric radar experiment



(a)

(b)

Fig. 9. Polarimetric experiment technique: (a) the scheme of the experiment, and (b) the received signals of four polarimetric combinations after pulse compression.

(1) Object and principle: The purpose of the experiment is to learn the polarimetric coefficients and their measurements. In the polarimetric experiment, the transceiver is operated simultaneously in two-channel modes. Two transmitting antennas and two receiving antennas connected to the inputs and outputs of the test kit, respectively, were used. Both the transmitting and receiving antennas included one antenna with a vertical polarization and another antenna with a horizontal polarization as shown in Fig. 9 (a). As a result, the above setup can be used to measure four coefficients S_{VV}, S_{VH}, S_{HV}, and S_{HH} corresponding to the four possible combinations of the channels. The four coefficients measured represent all the necessary information regarding the polarimetric scattering properties of the object.

(2) Experiment: The experiment is performed on a moving object (walking pedestrian). Students may play the role of the moving object. During the experiment, they can observe the radar signals from the four polarimetric combinations (VV, VH, HV, and HH) in real time.

(3) Assignment: Students compare the results from different polarimetric combinations and report the polarimetric coefficients of the detected objects. They plot the results of the four combinations of polarimetric measurements as shown in Fig. 9 (b). The four values of the 50 m range where the object is detected are polarimetric coefficient of the object.

5.5 Experiment 3: Polarimetric radar experiment

After three experiments, students were asked to write a research project proposal. Firstly, students write proposals and revise the topic through discussions. Then, weekly results of the research are added to the document. Students present weekly progress in class and have discussion with other students and instructors. Therefore, students' final submission is a combination of the proposal and the report. The students conducted the literature research and planed their research schedule. They added the content of the weekly research to the document every week. The specific details of students' research results are expected to be included in their own articles or patents. The representative topics and research results are as follows.

- (Topic) Fabrication of antenna using transparent conducting polymer—(Research results) Fabrication and measurement of the transparent antenna—(Major) Nanofabrication.
- (Topic) RF lens array antenna system for MIMO communication—(Research results) Design and simulation of the lens array antenna system for MIMO communication—(Major) Communication networks.
- (Topic) SAR imaging system—(Research results) System setup and implementation for SAR imaging experiment and imaging results of SAR on rail in anechoic chamber—(Major) Radar systems.

6. Assessment

6.1 Student assessment

Appropriate assessments increase the course effectiveness by confirming the educational achievements of the students and emphasizing the learning objectives [40, 41]. Similar to [10, 16], the assessments of the pulse compression results, laboratory project results, the presentation and the final written report are performed.

The assessment system for this course is shown in Table 2. The evaluation items and the corresponding LOs are described. Scores from 1–10 are assigned to the students for each entry. Seven students and a total of four instructors were involved in the course. A professor and two doctors participated as advisors, and a graduate student participated as a teaching assistant. Student answers to the questions related to each topic (50%), experimental ability (30%), and teamwork (20%) were evaluated. For pulse compression, experimental ability and teamwork were not evaluated because students did not carry out experiments on this topic.

In accordance to the main objectives of the course, radar research process is reflected in the evaluation method. The questions for each topic were based on a typical four-step radar system design process: system mission, design principle, implementation, test and verification. Student answers to the questions related to each topic were scored by the advisors on a scale of 1 (very poor) to 5 (excellent). Score 5 is given to a student who explains all four questions (mission, principle, implementation, test and verification) including the keyword. For each unexplained question, score 1 is deducted. This evaluation corresponds to LO1-3. An advisor and a teaching assistant participated in all the experiments, along with students and scored the experimental ability of the students, on a scale of 1 (incorrect and unsafe) to 3 (correct and safe). This evaluation corresponds to an LO4 assessment. Teamwork during the experiments is scored in terms of the degree of participation and the activeness of the students during the experiments was scored on a scale of 1 (insufficient) to 2 (sufficient). This evaluation corresponds to an LO6 assessment. The research project proposals were evaluated according to the four-step research process on a scale of 1 (very poor) to 5 (excellent). 5 points are given to the proposal with complete inclusion of mission, principle, implementation, test and verification. 1 point is deducted for each insufficient part. Integration of students' major to the topic, inclusion of background theory and proper setup of research requirements, completeness of required research steps, and clarity of tables, graphs, and analysis of the results were evaluated for mission, principle, implementation, test and verification, respectively. This evaluation corresponds to an LO5 assessment. LO7 is assessed by the evaluation of the written reports (50%) and presentations (50%) of the students. The integration and organization of the topics were scored from 1 (very poor) to 5 (excellent) for the report and the presentation, respectively. The clarity of the presented results of the experiments were scored from 1

Table 2. Assessment system

Criteria	**Related LO**
Pulse compression	
• Students' answers to following questions: Mission: Why pulse compression is performed? Principle: What is pulse compression? Implementation: How pulse compression is computed? Test and verification: Results of pulse compression. *Keywords*: matched filtering	LO1 LO2
Experiment 1: Range performance estimation	
• Students' answers to following questions (50 %): Mission: Why is range-Doppler processing performed? Principle: What is range-Doppler processing? Implementation: How is range-Doppler processing performed? Test and verification: Results of range-Doppler processing. *Keywords*: Doppler frequency and target velocity • Experiment (30 %): setup and execute correctly and safely • Teamwork (20 %): efficient role sharing and cooperation	LO3 LO4 LO6
Experiment 2: Monopulse radar test	
• Students' answers to following questions (50 %): Mission: Why monopulse radar is used? Principle: What is monopulse radar? Implementation: How to estimate the azimuth? Test and verification: Results of the azimuth estimation. *Keywords*: phase difference between the receive channels • Experiment (30 %): setup and execute correctly and safely • Teamwork (20 %): efficient role sharing and cooperation	LO3 LO4 LO6
Experiment 3: Polarimetric radar experiment	
• Students' answers to following questions (50 %): Mission: Why polarimetric radar is used? Principle: What is polarimetric radar? Implementation: How to measure the polarimetric coefficient? Test and verification: Results of the polarimetric measurement. *Keywords*: polarimetric characteristic of objects, orthogonality • Experiment (30 %): setup and execute correctly and safely • Teamwork (20 %): efficient role sharing and cooperation	LO3 LO4 LO6
Research project proposal	
Mission: Topics, ideas, and goal of project. Principle: Technical and theoretical background Implementation: Research ability, process of project. Test and verification: Results and analysis, efforts and progress	LO5
Presentation and written report	**Related LO**
Organization and completeness: the presentation and the report adequately integrates and organizes the topics and laboratory projects of the course.	LO7
Clarity and effectiveness: the presentation and the report displays and expresses the results of the laboratory projects using suitable plots and graphs.	LO7

(very poor) to 5 (excellent) for the report and the presentation, respectively.

The student assessment results for each topic are shown in Table 3. The average scores of the students were higher than nine through the entire entry. These results indicate that throughout the semester, students' achievement is consistently high for all topics without a decrease in student motivation. Therefore, student learning through the projects using the kit was efficient, and the students' achievement in the course content is satisfactory.

To analyze the achievements of the LOs, the student assessment results were classified by Each

Table 3. Student assessment results

Laboratory projects	**Average Score**
Pulse compression	9.67/10
Experiment 1: Range performance estimation	9.5/10
Experiment 2: Monopulse radar test	9.17/10
Experiment 3: Polarimetric radar experiment	9.17/10
Research project proposal	9.33/10
Presentation and written report	**Score range**
Organization and completeness	9.33/10
Clarity and effectiveness	9.67/10

Table 4. Percentage score for each LO

	LO1	LO2	LO3	LO4	LO5	LO6	LO7
Score (%)	96.7	96.7	92.2	96.7	93.3	95.6	95.0

Table 5. The survey questions and results of course evaluation

Evaluation question	Average Value
1. Satisfaction: Overall, this course was satisfactory.	4.85/5.0
2. Feedback: (1) The instructor(s) responded sincerely to questions. (2) The instructor(s) encouraged student participation.	 4.85/5.0 4.85/5.0
3. Intellectual Challenge: In this course, I was highly motivated to study the subject matter and related areas of study.	 4.85/5.0
4. Students Involvement and Quality of Effort: I was very involved and devoted much time and effort to this course.	 4.85/5.0
5. Change and Development: (1) Knowledge and/or understanding of the field of study (2) Problem-solving and/or ability to apply learning (3) Openness to diversity and different values	 4.71/5.0 4.71/5.0 4.85/5.0

LO. The averaged and percentage converted scores for each LO are shown in Table 4. Since all LO scores are greater than 90%, students have the ability to cover all LOs in this course. The high scores over 95% of LO4, LO6, and LO7 showed high achievement of practical skills such as experimental ability, data visualization and analysis, teamwork and presentation skills as well as theoretical achievement of students. It reflects the effectiveness of the experiments using the kit, since LO4, LO6, and LO7 are difficult to achieve through lectures in classrooms. These results accord with the course objectives, indicating that the course successfully achieved its objectives. The high score of LO5 shows that the design of the course for the purpose of convergence education has successfully helped students in diverse fields not only to gain knowledge about radar but also to apply that knowledge in their own research areas.

6.2 Course evaluation

A student survey was conducted for improving the course quality and syllabus based to the students' feedback on the course. The evaluation questions are provided by the university. The students' evaluation of the course was conducted anonymously, before the final report submission. The answers to the survey questions included ratings on a five-level scale from one (strongly disagree) to five (strongly agree). The survey questions and the averages of the students' answers are shown in Table 5. Since all scores are over 4.5 (90%), the students have positive opinions on the course. The high scores on student participation and motivation indicate that the design of radar laboratory course and development of a radar kit as an educational aid have successfully increased student participation by providing hands-on experience to students.

7. Discussion

The radar laboratory course applies PBL since the purpose of this course is not only to learn about signal processing algorithms or to do radar experiments, but also to achieve insights into the modern radar systems and to obtain the ability to perform radar research. A low-cost, easy-to-use sensor hardware has been developed as an educational kit for practicing radar experiments and signal processing algorithms. In a conventional laboratory course, the learning process is based on a set of given instructions. In this course, the students have the liberty to choose and write their own research proposals and do different kinds of radar experiments by taking advantage of the flexibility of the kit. Through this course, the students can apply their knowledge about radar systems into their own research areas, thus fulfilling the goal of convergence education.

All of the students, regardless of their major, successfully completed the research proposal. This reflects the enhancement of students' knowledge of the radar system operation as well as the process of conducting a radar research, which they learned throughout this course. For example, a student majoring in nanofabrication process proposed a research about radar antenna design using specific materials that they use in their research area. In the proposal, the research stages include antenna design and simulation, antenna fabrication, and antenna performance testing using the radar kit. Another student majoring in communication network proposed a research about multichannel processing which utilizes the multichannel function of the radar kit. Meanwhile, the students majoring in radar submitted research proposals about FPGA programming to implement the imaging function of the radar kit. Students interested in further study can use the kit for other applications and experiments and will qualify for additional achievements for their efforts. The main focus of this paper is to introduce the newly designed course and the educational kit, and to report the results of the course. In the future work, qualitative/quantitative assessment methods for cumulative analysis of the course from the results of several semesters would be considered and added.

Nowadays, various radars are produced in the form of chips and are easy to purchase. Radar is becoming a more common sensor rather than being used only for special purposes such as military or weather observation applications. Therefore, the proposed course design and the radar kit are expected to be applicable in the field of Internet of Things (IoT) which requires various sensor and wireless system technologies. Since IoT technology includes a comprehensive engineering fields, the content of this paper is not limited to radar technology or electrical and electronic engineering.

To achieve the expected outcomes of the course, both the hardware and software components of the provided radar kit should be accessible. In addition, the students need to know the various functions of the radar kit to be able to plan a research using the kit. Therefore, performing experiments 1, 2, and 3 described in section IV is mandatory, and the experimental results should be evaluated. The results of the experiments using the developed educational kit are shown as the example outcomes of the laboratory projects. Although the AD9361 chip is equipped with internal switches enabling the use of up to six inputs and four outputs, this feature is not implemented in the used evaluation board.

Based on the detection of an object at distance of 120 m, the range performance of the proposed system is comparable with the range performances of typical frequency-modulated continuous-wave (FMCW) sensors but the range resolution is degraded owing to the limitation in the transceiver bandwidth. However, unlike typical FMCW sensors, our system has the ability to resolve objects in the Doppler frequency domain.

The ZedBoard includes a one-year license for the FPGA development tools. Students may also obtain a free WebPack license (that supports the used SoC) for their personal use.

8. Conclusion

This paper has proposed a radar laboratory course for providing practical lessons on modern radar technologies. An expandable hardware and software kit for an educational PDR was developed and tested for effectively offering hands-on experience for the students. The application and effectiveness of experiments and PBL in a radar laboratory course were discussed. The efficient and student-centered education through the radar kits had led to the high achievements of all the students, despite their various backgrounds and abilities. Student assessment and course evaluation results indicate that the course objectives were successfully achieved. The design of the proposed course is expected to be applicable throughout engineering education where experience-oriented and practical education is required.

The possibility of using the proposed kit for facilitating the experimental study of radar signal processing fundamentals and modern trends in radar systems was demonstrated. The software structure of the kit permits an efficient extension of the programmable logic realization for forming and processing complex radar signals. Detailed information on the kit is presented to assist radar-technology educators.

As the kit is based on the software-defined radio, it can be utilized for multichannel modes and for changing the frequencies and bandwidths, owing to its flexibility. Therefore, the proposed system can not only be used for the three experiments proposed in this paper but can also be used for diverse educational programs. Therefore, the proposed course design and the radar kit are expected to be applicable elsewhere in the engineering field covering sensors or wireless systems, such as IoT. Further, the system has the potential to be used in practical radar systems such as the SAR, high resolution detection, and MIMO radars.

Acknowledgments—This research was supported by the MSIT(-Ministry of Science and ICT), Korea, under the ICT Consilience Creative program(IITP-2017-2017-0-01015) supervised by the IITP(Institute for Information & communications Technology Promotion); Civil Military Technology Cooperation Program; This work was supported by IITP grant funded by the Korea government(MSIT) (No. 2017-0-00678, A Development of SAR for small sized UAV).

References

1. D. E. Bolanakis, E. Glavas and G. A. Evangelakis, An integrated microcontroller-based tutoring system for computer architecture laboratory course, *International Journal of Engineering Education*, **23**(4), 2007, pp. 785–798.
2. D. M. Laverty, J. Milliken, M. Milford and M. Cregan, Embedded C programming: a practical course introducing programmable microprocessors, *European Journal of Engineering Education*, **37**(6), 2012, pp. 557–574.

3. B. E. Bishop, J. A. Piepmeier, G. Piper and K. A. Knowles, Low-Cost robotic laboratory exercises and projects, *International Journal of Engineering Education*, **22**(4), 2006, pp. 723–731.
4. H. Sumali, Developing a laboratory course in sensors and data acquisition for agricultural engineering, *International Journal of Engineering Education*, **22**(6), 2006, pp. 1231–1241.
5. C. V. Miguel, L. C. Matos, F. D. Megalhaes, L. M. Madeira and A. Mendes, Membrane ultrafiltration for oil-from-water separation: multidisciplinary lab experiment, *International Journal of Engineering Education*, **30**(1), 2014, pp. 254–262.
6. M. Jensen, D. Arnold and D. Crockett, System-level microwave design: Radar-based laboratory projects, *IEEE Transactions on Education*, **43**(4), 2000, pp. 414–419.
7. A. J. Camps, A radar course at undergraduate level: An approach to systems engineering, *IEEE Transactions on Education*, **46**(4), 2003, pp. 497–501.
8. M. Solano, J. Ipina, J. Zamanillo and C. Perez-Vega, X-band Gunn diode oscillator for a multiple-frequency continuous-wave radar for educational purposes, *IEEE Transactions on Education*, **45**(4), 2002, pp. 316–322.
9. A. V. Alejos et al., Educational system to approach teaching of bi-static noise radar, *Electronics and Electrical Engineering*, **102**(6), 2010, pp. 71–74.
10. M. Lumori and E. Kim, Engaging students in applied electromagnetics at the University of San Diego, *IEEE Transactions on Education*, **53**(3), 2010, pp. 419–429.
11. M. Yeary, T.-Y. Yu, R. Palmer, H. Monroy, I. Ruin, G. Zhang, P. Chilson, M. Biggerstaff, C. Weiss, K. Mitchell and L. D. Fink, Working together for better student learning: A multi-university, multi-federal partner program for asynchronous learning module development for radar based remote sensing systems, *IEEE Transactions on Education*, **53**(3), 2010, pp. 504–515.
12. N. E. Cagiltay, E. Aydin, R. Oktem, A. Kara, M. Alexandru and B. Reiner, Requirements for remote RF laboratory applications: An educators' perspective, *IEEE Transactions on Education*, **52**(1), 2009, pp. 75–81.
13. J. Jordana and F. J. Robert, A course on digital electronics based on solving design-oriented exercises by means of a PBL strategy, *International Journal of Engineering Education*, **31**(1), 2015, pp. 238–247.
14. C. Schroeder, M. Elahinia and M. Schumack, Integrating education and research: development of an hydraulic hybrid vehicle laboratory, *International Journal of Engineering Education*, **00**(0), 2008, pp. 1–12.
15. P. I. Muoka, M. E. Haque, A. Gargoom and M. Negnetvitsky, DSP-based hands-on laboratory experiments for photovoltaic power systems, *IEEE Transactions on Education*, **58**(1), 2015, pp. 39–47.
16. W. Lin, H. P. Yueh and J. J. Chou, Electronic pet robots for mechatronics engineering education: a project-based learning approach, *International Journal of Engineering Education*, **30**(1), 2014, pp. 231–239.
17. U. Hernandez-Jayo, J. Lopez-Garde, and J. Rodriguez-Seco, Addressing electronic communications system learning through a radar-based active learning project, *IEEE Transactions on Education*, **58**(4), 2015, pp. 269–275.
18. P. Bhatti and J. McClellan, A cochlear implant signal processing lab: Exploration of a problem-based learning exercise, *IEEE Transactions on Education*, **54**(4), 2011, pp. 628–636.
19. S. H. Jeong, H. Y. Yu, J. E. Lee, J. N. Oh and K. H. Lee, A multi-beam and multi-range radar with FMCW and digital beam forming for automotive applications, *Progress In Electromagnetics Research*, **124**, 2012, pp. 285–299.
20. T. Mitomo, N. Ono, H. Hoshino, Y. Yoshihara, O. Watanabe and I. Seto, A 77 GHz 90 nm CMOS transceiver for FMCW radar applications, *IEEE Journal of Solid-State Circuits*, **45**(4), 2010, pp. 928–937.
21. A. Meta, P. Hakkart, F. der Zwan, P. Hoogeboom and L. Ligthart, First demonstration of an X-band airborne FMCW SAR, In *Proceedings EuSAR*, Germany, 2006, pp. 1–4.
22. G. L. Charvat, Low-cost, high resolution X-band laboratory radar system for synthetic aperture radar applications, In *IEEE International Conference on Electro/Information Technology*, USA, 2006, pp. 529–531.
23. Y. Huang, P. V. Brennan, D. Patrick, I. Weller, P. Roberts and K. Hughes, FMCW based MIMO imaging radar for maritime navigation, *Progress In Electromagnetics Research*, **115**, 2011, pp. 327–342.
24. M. Pfitzner, F. Cholewa, P. Pirsch and H. Blume, FPGA based architecture for real-time SAR processing with integrated motion compensation, In *Asia-Pacific Conference on Synthetic Aperture Radar (APSAR)*, 2013, pp. 521–524.
25. Y. Wang, Q. Liu and A. E. Fathy, CW and pulse-Doppler radar processing based on FPGA for human sensing applications, *IEEE Transactions on Geoscience and Remote Sensing*, **51**(5), 2013.
26. Y. Kwag, J. Jung, I. Woo, M. Park, Modern Software Defined Radar (SDR) Technology and Its Trends, *Journal of Electromagnetic Engineering and Science*, **14**(4), 2014, pp. 321–328.
27. H. Zhang, L. Lin and W. Ke, 24GHz software-defined radar system for automotive applications, *IEEE European Conference on Wireless Technologies*, 2007.
28. Costanzo, S., F. Spadafora, A. Borgia, H. O. Moreno, A. Costanzo and G. Di Massa, High resolution software defined radar system for target detection, *Journal of Electrical and Computer Engineering*, **2013**(7), 2013.
29. J. Marimuthu, K. Bialkowski and A. Abbosh, Software-Defined Radar for Medical Imaging, *IEEE Transactions on Microwave Theory and Techniques*, **64**(2), 2016.
30. J. Park, N. Johnson, M. Majurec, E. Frankford, J. Culpepper, J. Reynolds, J. Tenbarge and L. Westbrook, Software defined radar studies of human motion signatures, *IEEE Radar Conference*, 2012.
31. Broadband Horn Antenna, LB-10180, Technical Specification. http://ainfoinc.com/en /pro_pdf/new_products/antenna/Broadband%20Horn%20Antenna/trLB- 10180.pdf, Accessed March 2016
32. Double-Ridged TEM Horn Antenna with Lens (GZ0226DRH). Technical characteristics. 2014, http://www.geozondas.com/description ams.php?pusl2=1&table=antennas table trans posed&id=7&option=1, Accessed March 2016
33. AD-FMCOMMS3-EBZ User Guide, https://wiki.analog.com/resources/eval/user-guides/ad-fmcomms3-ebz, Accessed December 2015
34. AD9361 Reference Manual, http://www.analog.com/media/en/technical-documentation/user-guides/AD9361_Reference_Manual_U G-570.pdf, Accessed December 2015
35. VME International Trade Association, "FPGA Mezzanine-Card (FMC) Standard", http://www.vita.com/
36. ZedBoard (2014) ZedBoard development kit, http://www.zedboard.org/product/zedboard
37. Xilinx, "Zynq-7000 All Programmable SoC Technical Reference Manual," 2015, http://www. xilinx.com/support/documentation/userguides/ug585-Zynq-7000-TRM.pdf.
38. B. R. Mahafza, Radar *Signal Analysis and Processing Using MATLAB*, Chapman and Hall, CRC, Boca Raton, FL, 2008
39. D. K. Barton, *Radar Equations for Modern Radar*, Artech House, Boston, Mass, 2012.
40. J. Bransford, A. Brown and R. Cocking, Eds., *How People Learn: Brain, Mind, Experience and School, National Research Council.* Washington, DC: Nat. Acad. Press, 2000.
41. L. Shuman, M. Besterfield-Sacre and J. McGourty, The ABET 'professional skills'—Can they be taught? Can they be assessed? *Journal of Engineering Education*, **94**(1), 2005, pp. 41–55.

Se-Yeon Jeon received the BS degree in IT convergence technology from Yonsei University, Seoul, Republic of Korea. She is currently pursuing the PhD degree with the School of Integrated Technology, Yonsei Institute of Convergence

Technology, Yonsei University. Her research interests include development for microwave sensors, electromagnetic wave signal processing, and synthetic aperture radars.

Konstantin Nikitin received the Engineer–Physicist qualification and the PhD degree from the Moscow Institute of Physics and Technology, State University, Russia, in 1998 and 2002, respectively. He is currently a Senior Researcher with the School of Integrated Technology, Yonsei Institute of Convergence Technology, Yonsei University, Korea. His current research interests include signal processing, microwave imaging, and synthetic apertures.

Aulia Dewantari received the BS degree in Telecommunication Engineering in 2012 from Institut Teknologi Bandung, Indonesia. She is currently a PhD candidate in the School of Integrated Technology and Yonsei Institute of Convergence Technology, Yonsei University, Korea. Her research interests include microwave radar imaging, thermoacoustic imaging, and antenna and transmission line design.

Sumin Kim received the BS degree in IT convergence technology from Yonsei University, Seoul, South Korea. He is currently pursuing the PhD degree with the School of Integrated Technology, Yonsei Institute of Convergence Technology, Yonsei University. His research area is development for microwave sensors, electromagnetic wave signal processing, and inverse synthetic aperture radars.

Min-Ho Ka received the BS and MS degrees in electronics engineering from Yonsei University, Seoul, South Korea, in 1989 and 1991, respectively, and the PhD degree in radio engineering from the Moscow Power Engineering Institute, Russia, in 1997. From 1997 to 2000, he was with the Agency for Defense Development, Ministry of Defense, South Korea, for the development of microwave imaging sensors, Spaceborne and Airborne Synthetic Aperture Radar. He worked at Korea Polytechnic University as a Professor, Head of the Department of Electronic Engineering, Dean of Planning Office and Deputy Director of the Korea-Russia Industrial Technology Cooperation Centre from 2002 to 2010. He is an associate professor with the School of Integrated Technology, Radar Systems and Wave Sensing Lab., Yonsei Institute of Convergence Technology, Yonsei University, and a chairman of Radar Group of Korean Institute of Electromagnetic Engineering and Science. His current research field is in system design and development of microwave sensors, and spaceborne and airborne synthetic aperture radar.