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RESEARCH ARTICLE

DEVELOPMENT OF AN EXPERIMENT SET FOR EMBEDDED SYSTEM EDUCATION AND ANALYZING ITS CONTRIBUTION

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ABSTRACT

In this study, a teaching material developed to provide application support to the theoretical expression of the embedded systems course in undergraduate and graduate education of engineering faculties is presented. The modular experiment set consists of STM32F4 Discovery microcontroller board and digital output, digital input, analog input, relay control, DC motor control, stepper motor control, alphanumeric LCD display, seven segment display and power distribution circuit boards connected to the board. The control software of the experimental set was developed using Waijung block sets in MATLAB / Simulink environment. The Waijung block set, which can be added to the MATLAB / Simulink library, allows the card to be programmed quickly and easily. At the same time, the program codes written by the user can be included in the developed model. With this experiment set, basic and some advanced embedded system applications can be performed. To research the availability of the experiment set in education, a group of undergraduate and graduate students was given the opportunity to use this set. Students were asked several questions about the experiment set and content analysis was performed on the answers obtained. In line with the data obtained, it was concluded that the experimental set developed eliminated a significant lack of material needed in the training of embedded systems.

Keywords: *Microcontroller Board, Embedded Systems, Engineering Education*

1. INTRODUCTION

Nowadays, the theoretical knowledge taught in vocational courses of engineering faculties should be supported by using appropriate educational materials in workshops and laboratory studies. The educational context presented in this way helps students reach the expected level of understanding and plays an important role in making the program successful and permanent [1], [2].

There are three different ways to use educational materials in vocational courses. The use of simulation programs is one of them. In the absence of a laboratory or experimental set, there are qualified simulation programs that can meet the need of students to make applications. Some of them are simulation-based computer programs such as Multisim, MATLAB / Simulink, MathCad, PSpice, Tina and SimQuick. In addition to these programs, there are simulation programs for electrical machines, computer system, signal processing, electrical circuits, microcontroller circuits which developed for special purposes. As these simulation programs do not have installation cost, system fault and system maintenance, they are quite useful. Simulation programs have some limitations as well as superior aspects [3]. Although these programs are designed close to reality, the data calculated in theory never completely correspond to the real data. This is because simulation applications are developed to estimate actual system behavior.

The other type of material used in vocational courses is the web-based experiment set. Web-based experiment sets are designed for use in distance education. Web-based training includes real-time and remotely accessible experiment sets. The remotely accessible experiment set can be controlled in real-time with the code the user sends online. There are many sets of web-based experiment in the literature. Ko et al. studied a web-based laboratory for control experiments on a coupled tank apparatus a with multiple inputs and outputs [4]. Chang et al. developed a virtual laboratory that allows PLC experiments [5]. Hurley and Lee presented a web-based power electronics laboratory [6]. Yılmaz et al. presented a real-time web platform project for robot control [7]. Stefanovic et al. developed a web-based laboratory that helps students with learning materials, science concepts and engineering principles [8–10]. Pulijala et al. presented a web based virtual laboratory for electromagnetic theory course taught at undergraduate level, which can be used as a didactic tool by teachers and as a self-learning tool by students [11]. Berm´udez-Ortega et al. presented a new approach to develop remote practices for Systems Engineering and Automatic Control laboratories based on Easy JavaScript Simulations (EJsS) Raspberry Pi and Node.js [12]. Kaçar et al. developed an internet based remote access experiment setup that could be used as a support material in engineering education for DC motor speed control with PID controller [13]. Jović and Matijević covered a topic on design and implementation of web-based laboratory for programming and use of an FPGA device [14]. Solak et al. developed, realized, and proposed a web-based virtual and remote laboratory environment for real-time control and monitoring of a mobile robot in an indoor environment [15]. Zia et al. proposed an underwater web-based testbed that evaluates the UW communication system in a controlled aquatic environment and simulates the UW channel and sound propagation models [16]. The main advantages of the web-based experiment sets are to eliminate the absence of applications in distance education and to reduce cost by using the common experiment sets by many people. Besides these advantages, the problems that arise due to multiple users trying to connect to the system at the same time and the necessity to always have a person near the experiment set to solve potential faults are the disadvantages of the web-based experiment set. Although simulation programs and web-based experiment sets are widely used in engineering faculties for electrical and electronics education, it is difficult to say that they are completely adequate for vocational applications. This is because some applications require direct student-lecturer interaction.

Interactive test sets are used as training materials in the formal education laboratory. Here, the student applies the concepts, commands and theories that exist in the context of the course in an effective and meaningful way under the guidance of the lecturer. In addition, their interest in professions increases by making different applications that improve their abilities. This is because the knowledge learned becomes permanent by seeing, hearing, and touching. There are interactive experiment sets prepared for different courses in the literature. Bay and Görgünoğlu presented an educational set specifically designed for teaching and learning the 8051 family microcontrollers[17]. Güllü and Kaplanoglu developed an experiment set for AC servo motor training [18]. Demir and Duran studied an embedded experimental set for digital signal processors [19]. Aldeyturriaga et al. presented a laboratory equipment that has been employed in experimental activities to code real-time PID control algorithms [20]. Ranjith et al. described the design of a novel do-it-yourself educational tool that is built using low cost materials, open source software and hardware, the designs for which are freely downloadable [21]. Alfonso et al. presented the design and implementation of a laboratory experiment for first year undergraduates of Bachelor of Science or Engineering degrees [22]. Sarı proposed an application of a PLC controlled system for practical education at electronics and automation laboratory [23]. Martinez-Santos described the development of courses in the field of digital design that use Arduino boards as their main platforms [24]. Bistak focused to the usage of the Arduino Uno platform for the measurement of static and dynamic characteristics of dynamical systems [25]. Aslam et al. presented designing of a software based 16-bit PIC24F series microcontroller educational trainer by using MPLAB and Proteus Professional software packages [26]. Apaydin and Serteller designed a 16F877 microcontroller training set for use in microcontroller courses [27].

In terms of cost and functionality, the presence of experimental sets created using the preferred products in the market in laboratories provides a great advantage to the students. At the same time, using up-to-date experimental kits helps students adapt more easily to the workplace environment. In this study, the design of an embedded system experiment set is carried out using the STM32F4 microcontroller board. The STM32F4 microcontroller board has been preferred due to its affordable cost, easy-to-use and high-end technical characteristics. Basic and advanced level electronic applications can be made with this embedded system experiment set. These are led blink, digital input-output, DC motor speed and rotation control, stepper motor speed and rotation control, alphanumeric LCD display, analog-digital converter, digital-analog converter and seven segment display applications. The experiment set is also suitable to be developed with the equipment that can be added later according to the need and level. The experimental set was made available to a group of 25 person, consisting of undergraduate and graduate students of the Department of Mechatronics Engineering at Karabuk University. And it has been concluded that STM32F4 experiment set is a beneficial educational material that can be used in the embedded system education based on feedback from users. In addition, this experimental set designed for use in the embedded systems course eliminates the absence of an important material.

2. EMBEDDED SYSTEM AND STM32F407VG Microcontroller Board

2.1. Embedded System

An embedded system is a digital system with processor and peripheral units. And these peripheral units are particularly designed to be solve a problem. In the embedded systems, specific, small, and more capable systems are used instead of general-purpose systems for the applications to be made. Unlike general purpose computer systems, these systems are specialized to perform one or more predefined tasks. Therefore, they interact with the user indirectly. The core of an embedded system consists of microprocessors or microcontrollers that are programmed to perform a certain number of tasks. Software programs are semi-permanent and named firmware in the embedded systems. They have a wide range of applications in many smart systems that we use in daily life such as mobile phones, copiers, bank ATMs, microwave ovens, washing machines and medical devices.

2.2. STM32F407VG Discovery Microcontroller Board

STM32F407VG is a microcontroller board developed with ARM7 structure and manufactured by ST Microelectronics. It has 1 MB Flash, 192 KB RAM and 32-bit ARM Cortex-M4F core. An SWD (Serial Wire Debug) connector is located on it for programming and debugging processes. It works with 5V supply voltage provided via a USB data bus or an external source. There are 3.3V and 5V supply outputs to be used in applications. LIS302DL, ST MEMS motion sensor, 3 axis accelerometer, MP45DT02, ST MEMS sound sensor, digital microphone, CS43L22 integrated D class speaker driver

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is also located on the card. Additionally, there are 8 LEDs, 4 of which are user- defined, and 2 buttons, one of which is user-defined and the other is reset.

One of the most important advantages of this board, which has 140 GPIO pins, is that the pin configurations can also be defined by the user. This advantage allows the user to use the pins on the board by defining them as digital input, digital output, analog input, or analog output in parallel with what user wants. Another feature of STM32F4 that makes it advantageous is "Hardware in the Loop (HIL or HWIL)" support. Hardware in the loop simulation is a technique used in the development and testing of complex real-time embedded systems. In this technique, a platform is created that will enable the embedded system to be designed effectively and easily. And mathematical models that reflect all the dynamics of the system are included in this platform. Thus, tests and designs are carried out as if a real-world system has been used and all scenarios that may occur in the real system are evaluated with this simulation. It is often used in the control of complex systems such as land vehicles, satellites, space vehicles, unmanned aerial vehicles, planes, weapon systems, submarines.

3. DESIGN OF THE EXPERIMENT SET

In this study, an experiment set is designed to ensure that embedded system is learned in a more effectively and easily. The experiment set consists of STM32F4 microcontroller board and digital input, digital output, analog input, relay control, DC motor driver, stepper motor driver, alphanumeric LCD display, seven segment display and power distribution circuit boards. In this experiment set, features of STM32F4 board such as ADC, PWM, digital input-output, analog input-output can be defined, and applications related to these features can be made. The developed experiment set is taken into consideration as hardware and software.

3.1. Hardware

Modular circuit boards that are connected to STM32F4 board are designed in a manner that they can be used with all microcontrollers. These boards that are located on the experiment set can be combined to be one or multiple on STM32F4 according to the performed applications. The designed circuit boards are given as below:

1. Digital Input Circuit Board: In this circuit board, there are 5 buttons. Meanwhile, the condition of the button (logic 1 or logic 0) can be observed with the LED that is connected to the pressed button on this circuit board. Digital input circuit board is given in Figure 1(a). Different types of control applications can be made according to the information read from the digital inputs on this card.

2. Digital Output Circuit Board: Digital data output from STM32F4 microcontroller board can be monitored through 8 different channels by using 8 units of LED on this board. Many applications like LED scroller, binary counter, BCD counter and Gray code counter can be performed with this circuit board. Digital output circuit board for LED applications is given in Figure 1(b).

3. Analog Input Circuit Board: Analog input circuit board has a potentiometer, an LM35 temperature sensor, an LDR (photoresistor) and an empty input for any analog measurement. The desired analog data is taken from the sensors on this board. It is then converted into digital data by the STM32F4 board, and some mathematical operations are performed on it. Such analog readings as humidity, temperature, wind speed and light level can be measure with this board which must be supplied by maximum 3.3V voltage. Analog input circuit board is given in Figure 1(c).

4. Relay Control Circuit Board: This designed circuit board is a digital output circuit board at the same time. Here, the purpose is to control the relays that are switching units that work at higher voltages with a voltage of 3.3V that is taken from the microcontroller board. The position of relays in the circuit can be observed with the LEDs that are connected to their outputs. With this circuit board, opening and closing control applications of a motor, a lighting unit or any electronic system can be made. Relay control circuit board is given in Figure 1(d).

5. DC Motor Driver Circuit Board: The transistors on this circuit board are H-shaped to make the "H-Bridge motor driver” logic understood and applied in an easier manner. In the H-Bridge motor driver circuit, transistor pairs are used which are conducted crosswise. The DC motor can be driven by PWM pulses. At the same time, the rotation speed of the motor can be measured with the speed sensor placed in front of the motor shaft. In Figure 1(e), DC motor driver circuit board is given.

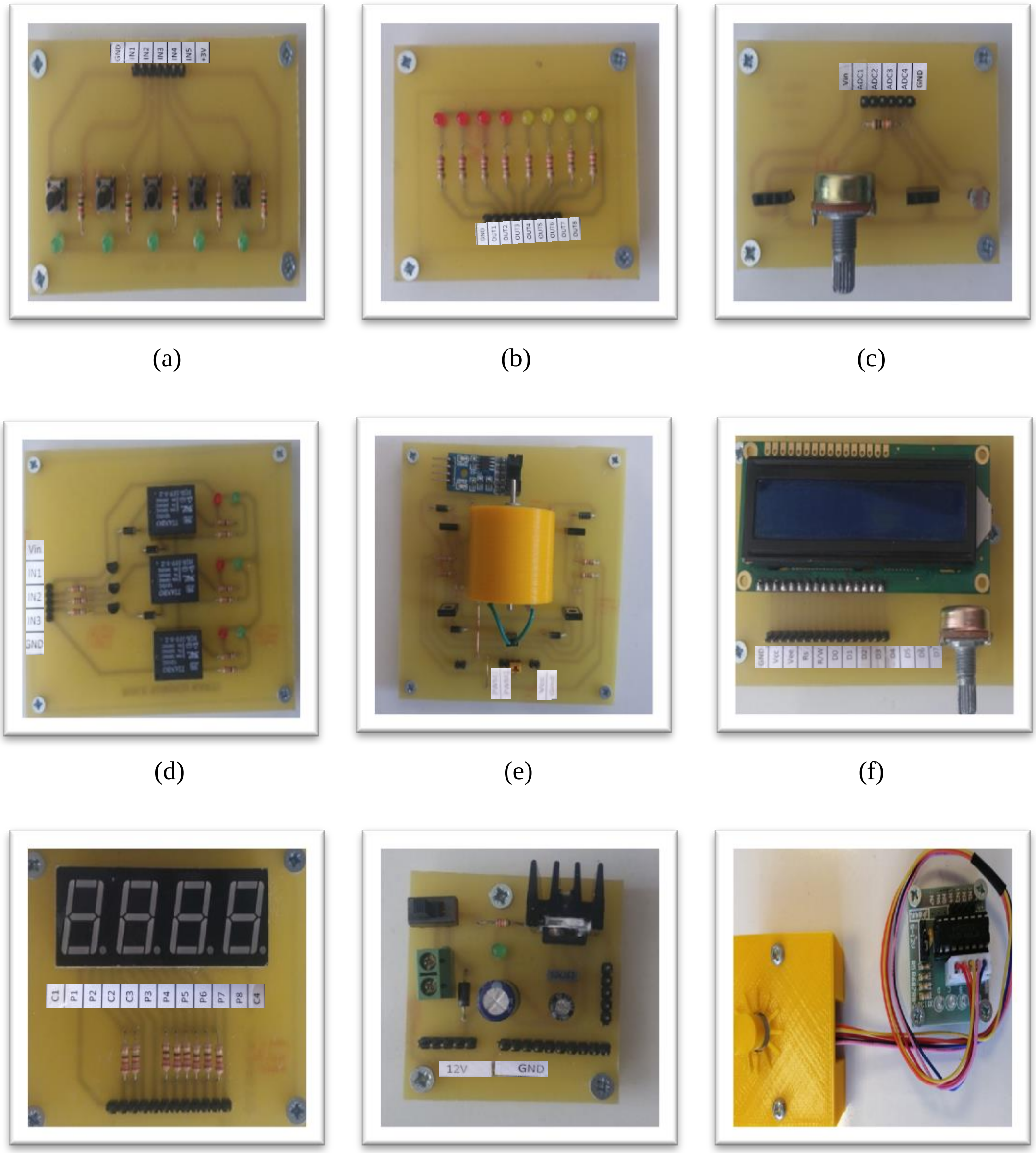
6. Alphanumeric LCD Display Board: This is a circuit board that is created to display the desired data like alert message, and user information or measurement values such as temperature, pressure, humidity, lighting level on the screen. Circuit board with alphanumeric LCD display is given in Figure 1(f).

7. Seven Segment Display Circuit Board: This is a display circuit board with seven LED units connected to the digital output pins of the microcontroller board. Since the display has a common anode connection, the shared pins of the LEDs are connected to the circuit’s (Vcc). And the circuit is controlled by connecting the cathode pins to the circuit’s (Gnd). It is designed to be a seven-segment display consisting of four units to suit many applications. Seven segment display circuit board is given in Figure 1(g). With this circuit board, digital date and time applications can be made.

8. Stepper Motor Driver Board: An ULN2003 stepper motor driver is used on this circuit board. The ULN2003 is one of the most common motor driver ICs that houses an array of 7 Darlington transistor pairs, each capable of driving loads up to 500mA and 50V. The stepper motor can be driven by four digital output of the microcontroller board with the ULN2003 IC. Stepper motor driver circuit board is given in Figure 1(h).

9. Regulation and Power Distribution Circuit Board: Since a constant voltage value is not used in each application of the experiment set, this circuit board is used to provide the required different voltage values. 12V received from SMPS is distributed to necessary places with the switches and pins in the regulation circuit. There are 5 pins of 12V, 5 pins of 5V and 10 pins of GND outputs. The LED on the regulation circuit shows whether there is energy in the system. Regulation and power distribution circuit board is given in Figure 1(i).

These boards designed for the experiment set are modular circuit boards designed to perform basic and advanced applications with the STM32F4 microcontroller board and to teach the hardware features of the card in this way. They can be added to the STMF4 microcontroller board in different combinations depending on the application requirement and are also compatible with other microcontroller boards. The overview of the experiment set is given in Figure 1(j).



(a) (b) (c)

(d) (e) (f)

(g) (h) (i)

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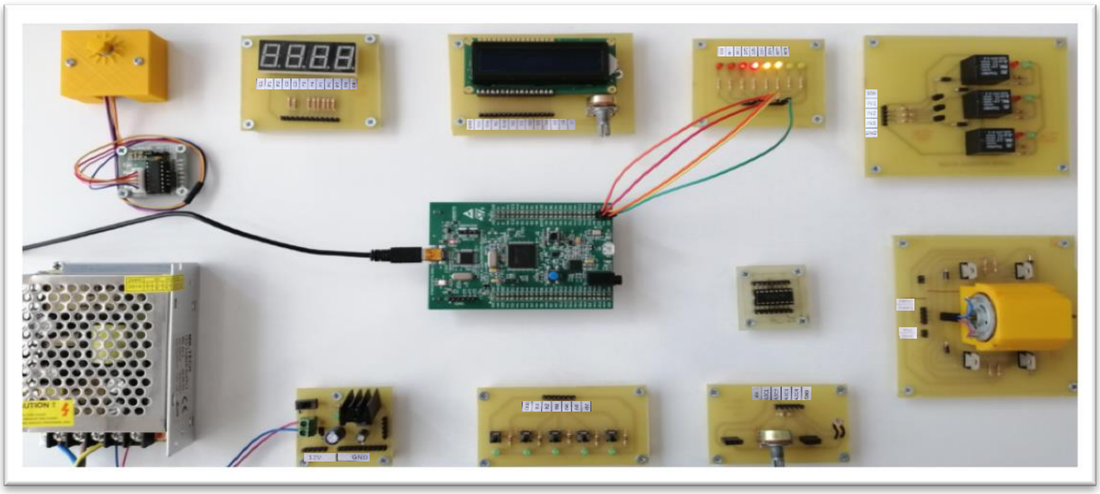

(j)

Figure 1. The developed circuit boards. (a) Digital output circuit board. (b) Digital input circuit board. (c) Analog input circuit board. (d) Relay control circuit board. (e) DC motor driver circuit board. (f) Alphanumeric LCD display circuit board. (g) Seven segment display circuit board. (h) Stepper motor driver circuit board. (i) Regulation circuit board. (j) Overview of the experimental set.

3.2. Software

In addition to being able to program the STM32F407VG microcontroller card produced by ST Microelectronics with programming languages such as C, C ++ and Assembly, it can also be provided with special package programs such as MATLAB / Simulink. MATLAB / Simulink provides a graphical environment for simulation and Model-Based Design of multidomain dynamic and embedded systems. In MATLAB / Simulink, main control applications such as system modelling, stability analysis, observation of system behaviors is carried out easily and with high accuracy. With Simulink block sets, basic concepts and theories can be taught more quickly and efficiently. Moreover, students can see the structure of a high-level system and can examine it.

With the compilation of the model developed in MATLAB / Simulink environment for STM32F4, the program files required for the embedded system are automatically created and loaded into the processor. For this purpose, the Waijung blockset is used in the study. Waijung blockset is a block set that is developed by Aimagin company that provides an option to make a Simulink-based application for its users. The “STM32F4 Target” block set included in Waijung blockSet is used to develop applications. Target Setup, Digital Output, Digital Input, Regular ADC, UART Setup, UART Tx, UART Rx, Timer IRQ, Basic PWM, Encoder Read blocks are the most used blocks.

The first step in developing applications with the Waijung blockset is to add the blockset to MATLAB/Simulink. The Waijung interface is used to compile a Simulink model created using the Waijung blockset. At the same time, the compilation process can be followed from this interface. To transfer code from the computer to STM, ST-Link Utility and ST-Link/V2 USB drives must be set up on the computer. The block diagram of code embedding process is given in Figure 2.

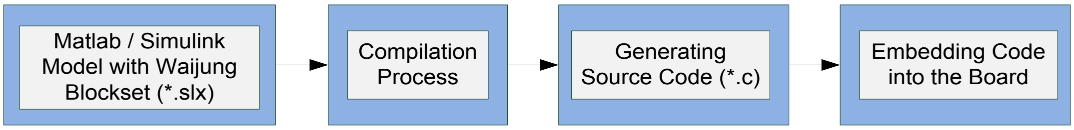

Figure 2. Block diagram of code embedding process.

It is possible to carry out many applications from basic level to advanced level in the created experimental set. The developed MATLAB / Simulink models with Waijung blocksets are given in Figure 3.

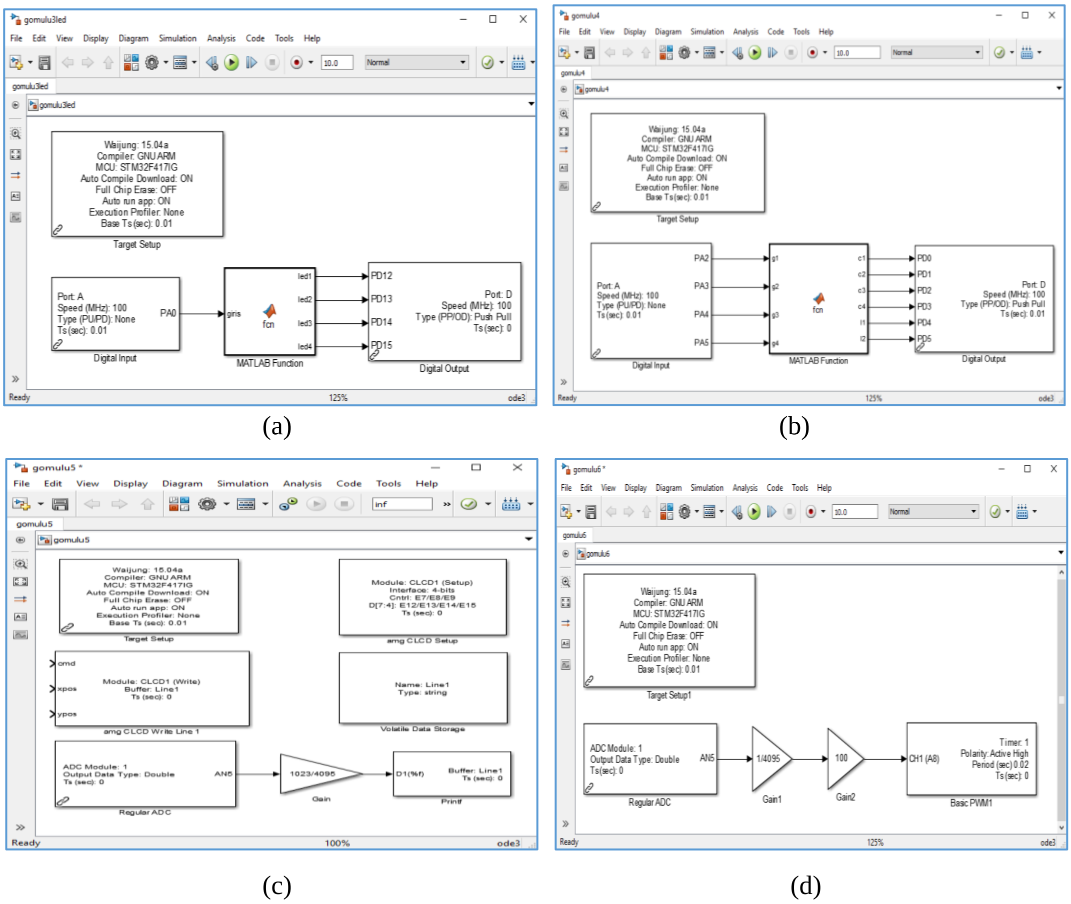

Figure 3. The developed MATLAB / Simulink models with Waijung blocksets. (a) Led - Button (Digital Input - Digital Output) application. (b) Seven segment display application. (c) Analog input and LCD application. (d) DC motor control application.

For example, if it is desired to create a LED scroller application, a new Simulink model screen opens in the MATLAB environment. While creating application model, the Target Setup block must not be forgotten, and the version used while making the arrangements must be selected. After configuring the

Waijung blockset, Digital Input and Digital Output blocks are placed on the model page. The pins that are desired to be used as digital input or output are defined. And a MATLAB Function block is added to the model to provide control between the digital input and digital output. The user can include own codes into the model with the MATLAB Function block. Similarly, many applications can be developed for STM32F4 board with the Waijung blockset.The developed model for led-button application is given in Figure 3 (a). In this application, the LEDs connected to the output according to the number of button presses are turned on respectively and then turned off. The developed model for seven segment display application is given in Figure 3 (b). In this application, in accordance with the data received from the digital input, the numbers shown from the seven segment display units are changed in the range of 0-9999. The developed model for analog input and LCD application is given in Figure 3 (c). In this application, analog data read from the potentiometer is seen on the LCD display. The developed model for DC motor control application is given in Figure 3 (d). In this application, the speed of the DC motor is controlled with PWM according to the analog value read from the potentiometer. In the developed models, Digital Input, Digital Output, Basic PWM, Regular ADC, amg GLCD and MATLAB Function blocks are used. Algorithms of applications are written to MATLAB Function block. All models and software developed are shared at https://drive.google.com/file/d/1dRbC6IHMVN62Vp2Uc2dymFMoXc1ZVe6l/view?usp=sharing

4. RESULTS AND DISCUSSION

The experiment set created in the study was tested with different MATLAB / Simulink and Waijung blocksets and it was seen that the system worked without any problems. To use the created experiment set, a group of 25 person, consisting of undergraduate and graduate students, has been formed in the Mechatronics Engineering Department. While determining the students in the group, they have a certain level of knowledge about electronics, circuit theory, system modelling, programming and the STFM2F4 microcontroller board. After the group of 25 person was created, a presentation was made explaining the use and purpose of the experiment set for all. In addition, a leaflet with explanations was given to each of them. As it is suitable for personal use, the students can make an application with the experiment set in the laboratory. In the studies conducted with the students, approximately 5 days were allocated to get the students' opinions and suggestions about the experiment set. Because these studies were planned for the times that were out of their lesson hours and each student was given 30-40 minutes to use and evaluate the experiment set. After allowing the students to use the experiment set, the following questions were asked:

1. Is it interesting to have a new (different) experiment set in the laboratory environment?
2. The use of MATLAB / Simulink and Waijung blocksets make the created application easier in terms of programming?
3. While making an application on the experiment set, do changing the parameters as you want and observe their results make any contribution to comprehend the subject that was taught in the lesson?
4. Do you think that you will use STM32F4 microcontroller card in your future projects, thesis, homework etc.?
5. Can learning STM32F4 microcontroller board’s hardware and software features be considered a preparation for the working environment after graduation?

When the answers to these questions that were asked to the students were evaluated according to the content analysis, the findings were grouped under the themes of usefulness, physical suitability, cognitive suitability, development, and creativity. The themes created because of the evaluated

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answers, the sub-themes created according to these themes and the frequency values calculated according to the scoring given are given in Table 1. In addition, graphical representation of experiment results also is given in Figure 4.

Table 1. The findings that were taken from the student views.

Theme	Sub-themes	f	%
Physical suitability	1. Raising interest and curiosity 2. Providing a usable environment	22 20	88 80
Productivity	3. Creating his/her own applications 4. Producing solutions	18 20	72 80
Cognitive suitability	5. Comprehension 6. Clarity	25 21	100 84
Utility	7. Usefulness 8. Raising awareness 9. Sense of success	25 22 24	100 88 96
Revenue	10. Success, happiness and increase in self-confidence 11. Contribution to the projects that they will take in the future	25 25	100 100
Creativity	12. Application development, production 13. Mental development, producing an idea	22 18	88 72

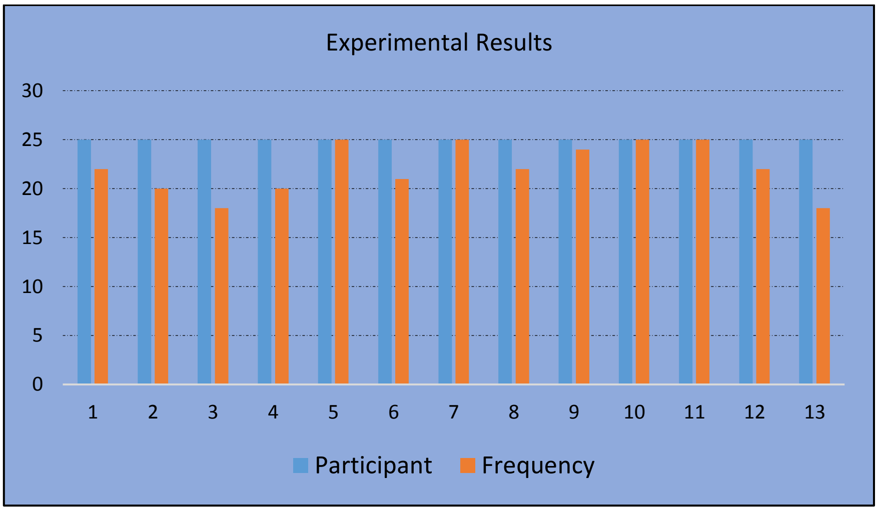

Figure 4. Graphical representation of experimental results.

According to the results obtained from the Table 1, it is concluded that the proposed material achieved an average success of 88,3% in these themes. Students stated that the existing experimental sets in the laboratory environment are out of date and the presence of an experiment set that allows the use of the

STM32F4 board raised interest and curiosity. It is understood from the given answers that this experiment set brings the characteristics of problem solving, establishing a cause-and-effect relation, analytical thinking and concreting of thoughts. Because it provides the opportunity for the students to create their own applications. They stated their views that no matter how good the theoretical teaching of the lesson is reinforcing the learned knowledge with application can create more persistent knowledge. Although the experiment set was seen for the first time, they stated that the applications that were needed to be made on the experiment set were understood quite clearly thanks to the preliminary information and distributed introductory brochures. They emphasized that making an experiment by changing as many parameters as they want during the experiment is quite instructive and allows them to observe the effect of each parameter change on the system. It was revealed that the experimental set was useful in achieving the intended outcomes and created awareness of modeling an embedded system. Most students stated that they do not prefer to use the STM32F4 microcontroller because they think it is more difficult and complex, but they can use it in applications for project-based lessons in the future. When students were told that the STM32F4 microcontroller board was the step to move to higher level processors, it was observed that students' concerns and prejudices about learning embedded systems decreased and their motivation to develop applications increased.

The created experiment set was designed to provide applied education support to the theoretical teaching of the embedded systems lesson that is in the curriculum of bachelor's and master's degrees. Thus, it is thought that it can be easier and more effective to learn the lesson and the absence of an important material that is needed in this field will be resolved by this means. In addition, STM32F4 microcontroller board, which is proposed to be used, will provide great convenience in the project-based lessons that they will make and the studies of their dissertations. As STM32F4 is a board that is preferred in the market, it will allow them to adapt easily to the working environment, when they graduate. Meanwhile, STM32F4 microcontroller board creates a basis for the high-level application developing boards such as DSP, Raspberry Pi and BeagleBone and makes it easier to move to these boards.

The experiment set has a modular structure and the applications that can be created are at the basic and advanced level. According to the students' knowledge level, the difficulty level of the applications, to be made, can be increased by diversifying the additional circuit boards that are added into the experiment set. The experiment set that is created in the study was planned to be used in the formal education. However, it can be made convenient for distance education by adding remote control modules to the study in parallel with the needs of today's education system. It was taken into consideration that the students interviewed were equivalent in terms of education and readiness levels. At the next stage of the study, it is planned to make the pretest-posttest application by benefiting from these data and a larger student group.

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