PROJECT-BASED LEARNING OF ROBOTICS FOR ENGINEERING EDUCATIONIMPROVEMENT

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ABSTRACT

Robotics is a multi-disciplinary field and is categorized as one of the toughest courses in the Mechanical Engineering Program (MEP) at Taif University (TU) according to the statistical analysis of the final grades. This multi-disciplinary subject in Engineering involves undergraduate students to go through some difficulties in the robotics theory and practice learning process, as undergraduate robotics courses suffer from lack of appropriate textbooks which cover either too fundamental concepts or too advanced topics and neglecting the combination of the theoretical analysis and the real applications. This motivated us to provide a Project-Based Learning (PBL) approach as an effective teaching technique into robotics course by using real robot projects. This approach is extending to cover the robotic theory topics and their application from different disciplines including Mechanical Design, Kinematics, Sensors, Automatic Control, Microcontrollers, Programming languages, and Software Algorithms Development. In this paper, two examples were provided of conducting the PBL approach into Robotics Course and how they were used to support and improve the teaching of all the robotics topics outlined in the course with system design and application until the later phase of construction. It was found that the PBL has served as an effective active-learning tool in improving the Student Outcomes(SOs) and motivating them to further study and research in robotics and that can be useful to help their local community by utilizing the prior courses' outcomes and robot theory to design real-time systems.

KEYWORDS: Project-Based Learning(PBL), Robotics, Engineering Education, Active Learning

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INTRODUCTION

The Mechanical Engineering Program (MEP) at Taif University (TU) has recently full accredited with American Accreditation Board (ABET) and rolled out a new curriculum, which ensures an active-learning educational environment in order to respond to the ever changing economic and social needs and provide student with the linkage between knowledge, hands-on skills and attitudes to design competitive systems, components or processes. This approach is provided to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability and sustainability, and also must be able to identify, formulate, and solve real engineering problems, [1].

The most remarkable change was including active and collaborative classrooms, [2-3], and student-centered teaching approaches in some courses of the MEP to foster, encourage and apply the basic hands-on

experience and experimental learning approach. As a result, the students acquired the essential and required soft and hard skills to solve most of the real engineering problems with high confidence, accuracy and efficiency. This method will enable students to be engineers capable to come up with real-time solutions of real engineering problems in their local community. Also, this type of education usually provide with necessary tools to made them able to be adapted to the engineering situations and environments more easily in the future by interacting with practicing their hands-on experience, which will not be the first time to deal with real challenging problems, [4].

Project-based learning or problem-based learning (PBL) is defined as a learner-centered approach that excites learners to conduct research, integrate theory and practice, and apply prior knowledge and skills to come up with a real-world solution to a well-defined problem. PBL technique helps students to be fully engaged in complex cooperative activities and focused on the creation of a product or performance, [5]. According to the current research, projects are complex tasks based on real-life problems. Projects usually includes organizing and driving activities, which taken as a whole amount to a meaningful project. When conducting PBL, teaching and learning environments include authentic content, authentic assessment, and authentic teaching facilitation. On the contrary, teaching direction, explicit educational goals, collaborative learning, and reflection are not included [6].

Robotics course (802204-3) is one of the courses in MEP at TU. This course was designed with an active-learning environment that uses the PBL as a teaching tool to educate the robotics theory and applications subjects presented in the course. The motivations of using PBL is because the robotic textbook for the undergraduate level is very difficult to find, instead, it can be found too basic or too advanced for the course objectives. Also, some textbook overlay simplified key robotics concepts and focused primarily on depth coverage of hardware, typically LEGOs[7,8]. Other textbooks present depth coverage of higher-level concepts in control and probability, neglecting the presentation of basic applications. still, there were other textbooks that are very fundamental or introductory and do not provide enough detail to implement the techniques on an actual hardware platform. Moreover, some textbooks consider some topics in the robotics subsystem as a complete course itself such sensory and actuating units. This diversity in textbooks with some topics such effectors, sensors, and actuators, which are too difficult to be understood theoretically created great difficulty in students' ability to master the material and apply it to the physical robot. The Authors felt that the PBL is the most sufficient and appropriate mean to teach the robotics principles which is guaranteeing to engage students in the course with a new interactive approach, [9,10].

In this Paper, a PBL approach was provided in the learning process to cover robotics course subjects that involves the use of principles and practices, of robotics. The main goals of this paper are:

- To design and develop a robotics course with a PBL approach to provide students with a synthesis and evaluation of engineering and science concepts learned in prior and current courses.
- To expose students to theories and challenges that robotics face such as sensory, odometer error, mechanical mechanism design, and bandwidth limitations.
- 3. To evaluate the effectiveness of the PBL approach implementation in multidisciplinary work that leads students to correct some common robotics misunderstandings and recruit students for researches.
- 4. To integrate multi-disciplinary engineering skills and soft-skills and hands-on collaborative learning experience in real-life problems.

In order to achieve these goals, a pick and place robot project used to pick an object with maximal weight 5 gram from one point to the another point. Another obstacle avoidance robot project can be used to avoid obstacles and maintain certain path to collect data and adapt information in order to bring out possible solutions of the presented problems. Moreover, these techniques are needed the most in the undergraduate study to enhance the most important student skills such as critical thinking, communication, creativity and analysis.

The Course Description

The Robotics Course (802204-3) was carried out in Spring 2018 for undergraduate-levels and is a (3- credit hours) course with an MEP prerequisite course called “Theory of Machine”. As one of the courses in the MPE curriculum, Robotics course was taken place in the last year as an elective course, typically for seniors, in order to connect the students’ prior academic learning outcomes to career mastery. The course highly emphasizes on the values and the ability to review, coordinate, and apply skills and outcomes of their prior undergraduate studies. The main purpose of this course is to improve students’ robotics skills through designing and constructing real robotic projects and increase their interest in learning by providing them with hands-on experience to bring real-world situations of real-life problems.

The Robotics course (802204-3) is composed of 30 hours lecturing and 30 hours practical experiments and laboratory activities. The course covered six major sessions, starting with basic concepts of robotics, design, and manipulation, to the particular topics of mechanical, electronic, control, sensory, and actuating engineering. These topics were scheduled progressively and distributed throughout 15 weeks, each week includes a lecture and accompanied by a laboratory session in order to recognize, apply, design, and improve the robotic subsystem concepts, the detailed topics explained in Table 1.

METHODOLOGY

This study presents the implementation of PBL approach into the robotics course in MEP Curriculum, where two robotic projects were allocated as the final artifact that was designed, developed and implemented. The methodology of this research is intended to provide the process and outcome of the course. The main focus was on the project team forming. Team forming depends on the instructor’s role in improving students’ learning process and outcomes in such an interdisciplinary subject like robotic.

Project Team Composition and Instructor Members' Roles

To conduct the PBL methodology in this research successfully students typically are divided into several groups of 4 students. A group composed of 4 students is suitable for the PBL approach active-learning environment. In this ways, students were asked to develop a proactive role in a comfortable learning environment, promote team-open discussions, provide the project details, and specify the role and responsibility of each member. The group forming helps students to make mistakes and learn from their mistakes. In such an environment, criticism, supports collaborative and cooperative learning are observed and considered as active learning tools, to encourages students work together, promote dialogue, develop the critical thinking, and exchange the skills and knowledge. The choice of these techniques contributed greatly to keep students motivated throughout the project.

Table 1: Course Content and Prior Related Courses in the Curriculum

Weeks NO.	Lectures Topics	Prior Related Courses	Activities
1-2	Introduction to Robotics - Robot definition. - Robot classification. - Robotics system components. - Notations Robot application.	Theory of Machines Machine Design	Brainstorming Team Work Frequent question
3-5	Manipulator Forward and Inverse Kinematics - Link coordinate frames Denavit-Hartenberg convention. - - Joint and end effector Cartesian space. - Forward kinematics transformations of Position. - Inverse kinematics of position. - Solvability. - Closed-Form Solutions. - Workspace.	Linear Algebra Theory of machines	Closed-book Quiz Home- exercise
6-8	Mechanics of Robot Motion - Translational and rotational velocities. - Velocity Transformations. - The Manipulator Jacobian. - Forward and inverse kinematics of velocity. - Singularities of robot motion. - Transformations of static forces and moments. - Joint and End-Effector force/torque Transformations.	Theory of Machines Linear Algebra	Assignments Workshop report Work in the Notebook
9-11	Robot Dynamics and Trajectory Planning - Lagrangian formulation. - Model properties. - Joint-based motion planning. - Cartesian-based path planning.	Vibrations System Dynamics and Control	Information search Work in the Notebook Closed-book Quiz
12-14	Robot Control - Independent joint control. - Feedforward control. - Inverse dynamics control. - Robot controller architectures. - Implementation problems. - Simulations.	System Dynamics and Control Programming I Electrical Circuits Electronics	Oral presentation Testing the System
15	Review	All course Topics	Open-Discussions Frequent Questions

The instructor had the greatest role throughout the project. The first and most important role was to guide students professionally by providing advice and experience, making the right decisions while managing the risk and uncertainty around the project. The second role was concerned with the project coordination monitoring the students' activities and supervising their work. The third role was to be facilitator and motivator to support and promote students' motivation throughout the project. The last one was to evaluate the acquired knowledge and skills throughout the project.

Learning Outcomes (SOS& SOIS) and Evaluation Methods

The topics of Robotics course (802204-3) have been carefully chosen and developed to ensure that they cover the introductory robotics concepts and theory level and satisfy the ABET core outcomes [11], which students have to achieve at the end of the course Table 2.

The course topics were dedicated to include practice and theory of robotics as well as achievable goals with fair management and investment in terms of times and efforts by the students within the time frame of one semester, 15weeks. The project outlines were made familiar to students from the beginning of the semester. In Addition of giving a brief description for the systems to be developed, the PBL emphasized that by the end of the course, students have to acquire the design, implementation and hands-on skills within given constraints and in accordance with several specified rules of requirements to achieve the Specific outcomes of instruction (SOIs) and Students Outcomes (SOs), which are articulated by the course and evaluated and recommended by ABET 2019.

The robotic course (802204-3) Specific Outcomes of Instruction (SOIs) are:

- Gain an understanding of Robot types, components and application.
- Learn the theoretical aspects of Robot direct kinematics.
- Learn the theoretical aspects of Robot inverse kinematics.
- Apply the basics of Robot Mechanics.
- Apply the basics of Robot Dynamics and Trajectory Planning.
- Learn how to Model and Control Robot Systems.

Course Assessments

The assessment of robotic course (802204-3) has been done based on direct and indirect assessments. In this method of assessment, students usually go through different types of assessments such as assignments, quizzes, laboratory reports, Mid-term I&II examinations. The course grade scale was weighting as follow: the Class performance [Attendance, participation, assignments, and reports] (weighting 5%), Course Project (weighting 20%), Quizzes (weighting 5%), Mid-term I (weighting 15%), Mid-term II (weighting 15%), and Final Exam (weighting 40%). The Mid-term I&II and final exams covered the whole course topics and contained questions that are more focused on the practical part. The quizzes in the lectures were provided in order to evaluate the students' ability to the integration of knowledge and understandings and showing the initiative taking in problems solving. To enhance the teaching capability, gain knowledge and improve the understanding of robotics subjects, students were asked to have a notebook throughout the lectures, tutorials, laboratories, and project work. The notebook contributed to the overall grade of the course as it supplemented the assignment work and confirmed students' overall competency. These Notebooks has been collected and assessed to emphasis on their importance during the project progress. The final project has been assessed based on the capability of the physical system to execute the main function and through the final report that allocates to provide students with the basic tools of research writing and strengthen their interest in further researches in the future.

Table 2: The ABET Students Outcomes (SOS), Related Performance Activities, and Evaluation Methods

SOS	Student Outcomes (SOS)	Student Performance Activities	Evaluation Methods
SO(1)	Ability to apply knowledge of mathematics, science, and engineering. An identify, formulate, and solve engineering problems	Mathematical modeling of the subsystems, Robots kinematics and dynamics, Practical electronics circuit design and theory. Students work in groups of four to construct the proposed projects.	Individual assignments. Group Open-discussion.
SO(2)	Ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability.	Students are responsible for design and implementation of robotics projects and integrated with electronic and control subsystem. Students must test, develop and improve their design in a simulated Observe-Conceive Design Implement Operate (O-CDIO) cycle, where the staff take the role of the local community and students must engineer a solution to the local community needs.	Group discussion and sharing resources. Working in notebook.
SO(3)	Ability to communicate effectively	The major project is to design and implement a robotics project in a group of four to develop their communication skills	Working in groups. Oral presentation.
SO(4)	Understanding of professional and ethical responsibility the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context and a knowledge of contemporary issues	Students have to consider the safety and appearance of their design, its performance and fitness to achieve the designed main function based on set of requirements and constraints and their community needs.	Group working. Open discussion and sharing resources.
SO(5)	Ability to function on multidisciplinary teams	Students develop their team work skills through group working.	Group working. Team assignment.
SO(6)	Ability to design and conduct experiments, as well as to analyze and interpret data	Practical implementation of Machine design, basic electronics, programming, testing, the (O-CDIO) design cycle, teamwork, and project management.	Fixed Experiments.
SO(7)	Recognition of the need for, and an ability to engage in life-long learning	Students work in groups of 4 to improve their long-life learning	Group working. Group Open-discussion

Design of the PBL in Robotics Course

PBL approach was implemented in MPE at TU and focused on the most five essential elements:

- The project ideas generating (a real problem that has a real-life application),
- Student-centered activities (well-designed learning activities and opportunities that motivate students to take initiative and ownership of the project and their learning),

- Substantial time (enough time to perform a meaningful work),
- Final Product (physical system, paper,...),
- The instructor role as monitor, facilitator, and motivator throughout the entire process.

To overcome the five elements related to challenges and the genuine nature of a multi-disciplinary project, students were arranged and guided to work in groups, and share knowledge and skills of robotics through designing, planning, and creating full- function robots and acquire the most essential resources to go on with the project. Students asked to execute the robot project while considering the issues of time, cost, financial support, and publicity. The instructor consistently followed the principles of PBL to ensure active-learning activities, including quizzes, information search, group work, individual assignments, and assessments for each team.

A robotic project with the PBL constructive approach was developed to focus on students' personal learning interests and motivations and ensures to engage learners in a complex and ill-defined context and improve their active involvement in the designing of a robot to do even a simple task can place extensive demands on students' creativity and problem-solving ability. Design and implementation of robot system projects are an ideal context for the PBL approach, where learners were involved with [12]approach shown in Table 3, in order to work collaboratively to define the problem, suggest applicable solutions and structure their artifacts. It is quite important that a 'driving' questions or sub/problem and open discussions set the stage and the project context, and guides to multiple artifacts. The result of this collaboration is the construction of an artifact that will be presented to a wider classroom audience. The production of an artifact, that is readily sharable with a larger community of learners, encourages students to make their ideas explicit, whilst allows them to experience science concepts in a meaningful and personalized context.

Table 3: Stages, Activities, Expected Results, and Devoted Teaching Strategies for the Implementation of A Robotic Project

Project Stage	Description Activities	Teaching Strategies	Expected Results
Engagement	Introduction of project selection. Finding out real-life application of the project. Group formulation.	Excite interest and curiosity. Open-Discussion. Brainstorming. Frequent questions.	Project Description. Open-ended issues.
Exploration	Study specific topics and concepts. Acquire knowledge and principles. Gain soft and hard skills.	Guided exploration. Experimentation. Practicing skills.	Product with specific function execution.
Investigation	Formulate question/questions. Plan and perform an investigation.	Experimentation. Presentation.	Arising Questions/problems.
Creation	Planning. Construction. Modeling and Testing.	Independent research. Experimentation. Creation.	Group-based solutions of defined problems. Taking notes.
Evaluation	Oral Presentation. Self-evaluation of groups and individuals. Peer evaluation.	Presentation Evaluation.	Provide physical system and final report.

Projects Procedures

The PBL procedures followed of selecting, designing, and implementing the projects is illustrated in Fig.1, depending on the Observe-Conceive>>Design>>Implement>>Operate (O-CDIO) model, which is based on a well-established engineering education structure called CDIO, and is emphasizing the engineering process cycle, Conceive>>Design>>Implement>>Operate. O-CDIO focuses on the problem-solving process and the design thinking Methods [13]. The procedures start by defining a common real problem in the local community by the students (**Conceive Stage**). After that, designing the physical system from scratch and designing the mechanical structure, CAD prototype, electronic circuits, and the controller for the system (**Design stage**). Then building the designed system and implement the controllers and programming codes on the sensor and actuators subsystem units of the whole system through the MATLAB/ Simulink and Arduino microcontroller software platforms(**Implement Stage**). After that, testing the subsystems validation running the system and study the whole system performance (**Operate Stage**). Eventually getting the feedback and improve the design performance through the design- implement process (**Observe Stage**).

The projects ideas were generated basically by students and approved by the instructor, in fact the instructor felt that robotics can bring a real-time solution for most of real-life problems and retain the students' enthusiasm to be problem-finders not only problem-solvers[14-15]. In the first lecture, the instructor provides the students with robotics definition, robots type and a video-tape of real-life robots designed to be capable to solve a set of typical problems, which motivated students to engage in the class-activities in more effective way and extend their conception to come up with a unique set of projects ideas. Students also were encouraged to participate in depth by allocating a reasonable percentage of marks to the project as it will make them devoting most of their studying time and efforts in the class and outside the class into the projects. Teams of students (Groups) were formed, and the general projects instructions were handed out to them. Each team was asked to perform the following tasks:

- Set a real-life problem that can be typically solved with robotics and provides a real-time solution.
- Propose a real system structure that can be brought to real with taking account of the constraints and requirements and provide the flowchart.
- Construct and assemble the system physically based on O-CDIO Engineering Cycle.
- Perform a mathematical model for the robot and its subsystems.
- Perform the conceptual design, CAD design, wiring circuit, programming code, and the software flowchart.
- Design a controller with feedback loop and perform the tuning technique for the best controller parameters (K_p , K_i , and K_d).
- Study the system performance by integrating the electrical components, mechanical structure, electronic circuit design, the designed controller, and the developed algorithm programming of the system.
- Provide a notebook to take notes in the lecture, tutorials, and labs, for the projects' documentation purpose.
- Submit a final technical report that illustrates the whole process.

The Projects Selection Methodology

The First laboratory session is dedicated to teach students the tools required to effectively communicate and carry out the brainstorming in order to create a set of projects ideas and thoughts taking the selection criteria in consideration as shown in Fig.1. The projects selection methodology was controversial and had the following procedures that students must follow:

Individually, every student should prepare a set of projects ideas by searching in the web or an idea for solving a presented problem in his community. The emphasis is put on the project ideas, where ideas should have a real-life application and can be used to bring a real-time solution for a real-life problem.

Team, every team of students have to arrange a meeting to show their individually projects suggestions and use the boggle method to eliminate duplicated ideas and Affinity method to organize the remaining ideas into common categories ending up with a unique set of ideas of their suggested projects.

Instructor, the boggle method is used with all team in order to come up with a specific unrepeated project. Then the suggested project of each team is announced in the class and written in the board for publicity.

Team, each group held a short discussion about the project design and implementation process. A collection of thoughts is generated keeping only the projects meet with constraints. The opted projects should be model with simple real structure and to use as a teaching tool in Collage of Engineering at Taif University.

Team, each team is assigned within final project based on their desire and preference.

Projects Structure, Scale Grade and Assessments

The project's weight was **20%** from the total course grade system and was distributed as in Table 4. All the assessments were concerning to the robot projects, and pursue the six main stages of a robot projects design process, where the first assignment is the project proposal which emphasizes on the context and problem understanding and covers the Engagement stage, The second assignment is the exploration of design concepts, The third assignment is the creation of design concepts, The fourth and fifth assignments are the investigation of the project design process, and the last assessment is an evaluation of the most appropriate solution.

Table 4: The Projects' Assignments, Weighting, and Evaluation

Assignments	Evaluation	Weighting (%)
Project proposal	Team	10
Concept design assessment	Individual	15
Detailed design	Team	15
Oral presentation	Individual + Team	20 (5+15)
Notebook& self-reflection	Individual	10
Final project report	Team	30

The Final report is allocated to guide student to grasp the most essential elements in the writing of technical report and improving the writing skills that some students has to acquired and utilize them to write their own published papers[16].

The Final report structure should contain:

- Abstract.
- Mathematical modeling.

- Controller design.
- The experimental work.
- Results and discussion.
- Conclusion.

Figure 1: Projects Procedures Flow Chart

Students Projects

During the implementation of these projects many workshops were held to guide and monitor the students to conduct the Conceptual design, The Mechanical structure design, the controller design, the electronic circuit design, and the programming code of the robot system Fig. 2. These workshops were executed in the Production Technology and Control & Robotics laboratories by applying the outcomes of the acquired knowledge and skills from the prior courses in the curriculum such as Production Technology, Theory of Machine, Material science, electronics, System dynamics and control, and Production Engineering. Students were provided with the laboratories Safety instructions and they must be careful when it comes to the lathe machine and the arc welding by dressing all the safety items available in the laboratory. The authors emphasized the importance of laboratory practice in engineering for long-life learning [17], where many challenging problems and troubles were faced by Students during the design, build, and integrating the process and acquired the problem-solving skills. These projects were developed based on the above methodology and implemented in the MPE at TU, Saudi Arabia during spring 2018.

Figure 2: Robotics Projects Workshops

Pick and Place Project

The general idea of the project selection was to emphasize on the role of the robotics in the industry field. Most production lines in the industry used robot manipulations to perform most of the industrial and exhausting tasks such as picking and placing objects, components assembly, and all the movements that are handled by a fully-functioning human arm. The main function of this project was determined to perform the take and place operations with two degree of freedom robot arm.

The CAD prototype was developed using SolidWork as shown in Fig. 3. Students suggested for the materials selection of the robot body Design were from iron and Aluminum Alloy, where the Base made from the iron in order to be heavy and also should be sufficiently wide to prevent the system from falling over, and the arms made from the Aluminum Alloy because of their availability in the community and to reduce the load on the actuators, which are two stepper motors used to energize the two revolute joints. The end-effector design was a controversial, one suggestion that instructor provided and students agreed, was an electromagnet gripper design, where students guided to apply the physics concepts of the electricity and magnet to design a simple, effective electromagnet gripper.

Table 5: The CAD Prototype Design of the Pick and Place Robot System

Component	2D dimensions(mm)	3D Dimensions
Base
Shaft
Arm 1
Arm 2
The Final Design Assembly

The next step was purchasing and ordering the components and materials to start implementing the mechanical structure design of the project. At the same time, a set of followed workshops and tutorials modules were presented, providing the students with the mathematical model of the robotics system. The main function of the mathematical model is to define the models needed during the design of the optimized projects including Kinematics, dynamics, and actuating subsystem and the controller design. As well as, Mathematical modeling represents the use of mathematics into the real robot system for testing, examination, and validation of the subsystems that is needed to enhance the understanding and implementation of reliable robotics system. In our case, students were developed the mathematical model of the robotics subsystems through the study of Kinematics model, dynamics model, actuator model, and control system model.

The Kinematics model as shown in Fig. 4. Was performed including frames attachment, the homogenous transformation matrices between the frames, Denavit-Hartenberg Convention (DH) parameters in, and the position coordinates of the manipulator end-effector through Eqs. 1-3, and the desired angles through Eqs.4-6. This modeling approach provides a simple mathematical procedure for finding the current robot position in space based on the frames transforming and the related angles to reach this position when the current position is known.

DH-parameters of the RR robot arm				
Link	a_i	α_i	d_i	θ_i
1	L_1	0	0	θ_1
2	L_2	0	0	θ_2

$${}^0_2T = \begin{bmatrix} \cos(\theta_1 + \theta_2) & -\sin(\theta_1 + \theta_2) & 0 & L_1 \cos \theta_1 + L_2 \cos(\theta_1 + \theta_2) \\ \sin(\theta_1 + \theta_2) & \cos(\theta_1 + \theta_2) & 0 & L_1 \sin \theta_1 + L_2 \sin(\theta_1 + \theta_2) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

$$Px = L_1 \cos \theta_1 + L_2 \cos(\theta_1 + \theta_2) \quad (2)$$

$$Py = L_1 \sin \theta_1 + L_2 \sin(\theta_1 + \theta_2) \quad (3)$$

a. Forward Kinematics

$$p_x^2 + p_y^2 = L_1^2 + L_2^2 + 2L_1L_2 \cos \theta_2 \quad (4)$$

$$\theta_2 = \pm \operatorname{atan} \frac{\sin \theta_2}{\cos \theta_2} \quad (5)$$

$$\theta_1 = \operatorname{atan} \frac{\sin \theta_1}{\cos \theta_1} = \operatorname{atan} \frac{(L_1 + L_2 \cos \theta_2)p_y \pm L_2 \sin \theta_2 p_x}{(L_1 + L_2 \cos \theta_2)p_x \pm L_2 \sin \theta_2 p_y} \quad (6)$$

b. Inverse Kinematics

Figure 4: The Kinematic Model of the Pick and Place Robot System.

As the determination of motion equations is a significant step toward designing the control structure of the robot system, students performed the dynamic model using the Euler-Lagrange method which depends on the kinetic and potential energies through Eqs. 7,8 as illustrated in Fig. 5. The dynamic model is important to figure out the forces involved in the robot arm and established a mathematical relationship between the location of the robot joint variables and the dimensional parameters of the robot.

$$F = \frac{d}{dt} \left[\frac{\partial \mathcal{L}}{\partial \dot{\theta}} \right] - \frac{\partial \mathcal{L}}{\partial \theta} \quad (7)$$

$$KE = \frac{1}{2}(m_1 + m_2)l_1^2 \dot{\theta}_1^2 + \frac{1}{2}m_2l_1^2 \dot{\theta}_1^2 + m_2l_2^2 \dot{\theta}_1 \dot{\theta}_2 + \frac{1}{2}m_2l_2^2 \dot{\theta}_2^2 + m_2l_1l_2 \cos \theta_2 (\dot{\theta}_1 \dot{\theta}_2 + \dot{\theta}_1^2)$$

$$PE = m_1gl_1 \cos \theta_1 + m_2g(l_1 \cos \theta_1 + l_2 \cos(\theta_1 + \theta_2)) \quad (8)$$

Figure 5: The Dynamics Model of the Pick and Place Robot System

The pick and place robot system was actuated by two DC motors (Steeper motors), each has an Electrical part and a Mechanical part. By using Newton's law, Kirchhoff's law and Ohm's law, students were able to **mathematically described model** of each of the two motors Fig. 6, and determine the transfer function (Eq. 9).

Figure 6: The Mathematical Model of the Actuator Subsystem.

The equation of motion Eq.11, that derived from the Euler-Lagrange method is a nonlinear equation and has an unknown applied torques into the robot. **The mathematical model of controller design** was required as shown in Fig. 7, by using Eq.10 the Force applied of the joints was controlled to reach the final position. Students used the classical linear PID, Particularly Two PID controls were required since the first arm motion is dependent from the second arm motion.

$$\begin{aligned}
 F &= K_P e + K_D \dot{e} + K_I \int e \, dt \\
 F &= K_P e + K_D \dot{e} + \xi \\
 B(\ddot{q}) + C(\dot{q}, q) + g(q) &= K_P e + K_D \dot{e} + \xi \\
 \begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \end{bmatrix} &= B(q)^{-1} [-C(\dot{q}, q) - g(q)] + \begin{bmatrix} K_{P1}(\theta_{1f} - \theta_1) + K_{D1}\dot{\theta}_1 + \xi_1 \\ K_{P2}(\theta_{2f} - \theta_2) + K_{D2}\dot{\theta}_2 + \xi_2 \end{bmatrix}
 \end{aligned} \tag{10}$$

Figure 7: The Controller Design of the Pick and Place Robot System.

The Mathematical Modeling of robotics system and application to the real-world systems, in our case on the serial robot, enables us to provide new ways of delivering knowledge and skills about robotics theory. This way of providing knowledge encourages students to enhance their abilities to study the modeling of the robotics systems and excite their interests in working in scientific researches fields.

The Sub/Systems simulation of the robot system was performed using MATLAB/Simulink software platform. Modeling and simulation have a very essential role in the realization of the robotics system prototypes and provide a more realistic validation of the robotics systems behavior and control performance. The analysis of the simulation leads students to observe whether the system behavior is enough stable and ensures that the motors have no high jerk (acceleration) at the start working, which is related to the applied torques and angels errors.

The single link simulation was a very important step to study the dynamic response of the link and the related torque and theta errors. Students tested the validity and the savior of the proportional- Integration- Derivative (PID) controller into the system in order to ensure the best system characteristic values and the sufficient time for the system to reach the steady-state error. The best system characteristics ($K_P = 40, K_I = 13, \text{and } K_D = 5$) were obtained after the manually tuning as illustrated in Fig. 8 and 9.

Figure 8: The Single Link Simulation With PID Controller.

Figure 9: The Single One Link PID Controller Response.

The whole robot system simulation was performed through the MATLAB/Simscape physical system modeling and simulation platform. The Simscape was used for exporting the CAD design from solidworks into MATLAB software platforms in order to simulate the real physical system and developing the controlling unit as illustrated in Fig. 10.

Figure 10: The 2-DOF Planar Robot Arm MATLAB/Simscape.

The MATLAB/Simechanics library [18] blocks were used to provide the two revolute joints robot (2-DOF) system with the actuating and the sensory units, where each joint was supplied with the joints initial conditions for the actuating unit and two sensors for torques and angels for sensory unit as shown in Fig. 11, 12, 13. The system simulation results showed that the system is nonlinear.

Figure 11: MATLAB/Simechanics of the 2-DOF Planar Robot Arm.

Figure 12: The 2-DOF Planar Robot Arm Nonlinear Response (Position Error).

Figure 13: The 2-DOF Planar Robot Arm Nonlinear Response (Torque Error).

The linearization Simulink model was performed as shown Fig. 14, 15, where the step function and PID control blocks were added to the model. As the results are clearly shown that the dynamic response of first link which has much inertia takes longer time to follow the desired trajectory.

Figure 14: The 2-DOF planar robot arm with PID controller.

Figure 15: The 2-DOF Planar Robot Arm Linear Response.

The Wiring circuit of the robot system was developed using Fritzing software Fig. 16. Before the wiring circuit was done, students were asked to acquire the skills of the reading and understanding the electronic components data sheets to know the working principles of each component.

a. schematic diagram

b. wiring circuit

Figure 16: Wiring Circuit of The Pick and Place Robot System.

For the controller unit, which was the heart of the robot system, as all vital kinematic and control calculations were performed by it. Students used for this project an Arduino Uno board microcontroller, check [19] and Two L298N drivers, check [20] to connect the motors with the microcontroller for executing the programming code by sending a PWM to the motors through the microcontroller.

The last workshop in the project optimization was performing, developing, and executing the programming task. Students started programming the microcontroller which is here an Arduino Uno board for ease of operation. The programming code was developed using the Arduino IDE software, which supports C/C++ programming languages. Students utilized the C++ for creating classes and installing their own libraries inside the Arduino IDE software, where two libraries were developed one for the motor called motor and the second for the gripper called gripper as shown in Fig. 17.

```
//
#include "motor.h"
#include "gripper.h"

void loop() {
    // put your main code here, to run repeatedly:
    motor M1 ,M2;
    gripper G;
    M1.Right(400,3);
    M2.left(500,8);
    G. pick(200,1);
    M2.Right(600,10);
    M1.left(300,9);
    G. place(300,2);

}
//////////
```

Figure 17: The Classes of Motor and Gripper.

The working principle of the project software was developed through the flowchart as shown in Fig. 18. This flowchart gives the summary of the project main function execution, which is the take and place operations, where the robot system has two revolute joints and well-defined take and place positions.

The Robot subsystems were integrated, tested and implemented to execute the pick and place operations of metallic objects within a weight (<30 grams) and control the robot movement to reach the desired position Fig. 19. During the operation stage, we have noticed that this movement was not typically smooth and the motors sometimes do not have a sufficient torque when the load is heavy resulting in a precision error with (+/- 1cm) in the x-axis and y-axis respectively.

Figure 18: Pick and place Robot System Software Flowchart.

Figure 19: The Integrated 2-DOF Pick and Place Robot System.

Obstacle Avoidance Robot Project

An open-discussion was held for the project general idea generation, which was to solve a real-life problem in the community with Mobile Robot Applications (MRA) and cover the most theoretical and practical topic's concepts in the robotics [21,22]. Students believed that, the obstacle avoidance robot can be regarded as real-time solution of the high-ratio of the accidents death percentage in the community. The main function of this project was obstacle avoidance Fig. 20 which is an introductory-level robot developed for engineering education and profession promotion campaigns at schools and colleges and to supply the robot with software and hardware platforms. Students started building up the physical system and assembled the system components by using the outcomes of the Fundamental of Electrical Circuits, Programming I, Electronics, and System dynamics and control courses had taken prior in the curriculum, which enabled them to come over many challenging difficulties related to the mechanical design, electronic circuit, sensory unit, wiring diagram, and programming and debugging.

Figure 20: The Obstacle Avoidance Robot System.

The Mathematical model was performed to enhance student's ability of applying the knowledge of Mathematics, Science, and Engineering which reflects on students' performance later in developing the mathematical model of the robotics system. In this project, students developed the mathematical model of robotics through the study and analysis of Kinematic model, Dynamics model, Actuator model, and the robot controller model.

Kinematics is very essential in studying how the robot mechanical system is working. In mobile robotics, kinematics formulation Eq. 11 and Eq. 12 are a significant step toward understanding the mechanical behavior of the robot in order to be able to design appropriate mobile robots for various tasks and also, to design a control software and integrate with the mobile robot hardware to execute its main function Fig.21.

$$\omega^k = \begin{bmatrix} \omega_1(t) \\ \omega_2(t) \\ \omega_3(t) \end{bmatrix} = \frac{1}{r} \begin{bmatrix} v_1(t) \\ v_2(t) \\ v_3(t) \end{bmatrix} = \frac{1}{r} \begin{bmatrix} -\sin(\phi_1) & \cos(\phi_1) & R \\ -\sin(\phi_2) & \cos(\phi_1) & R \\ -\sin(\phi_3) & \cos(\phi_1) & R \end{bmatrix} \begin{bmatrix} \dot{x}_r(t) \\ \dot{y}_r(t) \\ \dot{\theta}(t) \end{bmatrix} \quad (11)$$

$$\begin{bmatrix} x_v(t_1) \\ y_v(t_1) \\ \theta(t_1) \end{bmatrix} = \begin{bmatrix} x_{v,0} \\ y_{v,0} \\ \theta_0 \end{bmatrix} + r \int_{t_0}^{t_1} ((T_{k \rightarrow v})^{-1} \begin{bmatrix} \omega_1(t) \\ \omega_2(t) \\ \omega_3(t) \end{bmatrix} dt) \quad (12)$$

Figure 21: The Mobile Robot Kinematic Model.

Knowledge about the **dynamics** of mobile robots is a very important step for planning feasible mobile robot

trajectories and for determining the motion equations to facilitate the controller structure design of the mobile robot as Eq. 13 and Eq. 14 were illustrated in Fig. 22.

$$\begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} rv \\ -ru \\ 0 \end{bmatrix} + \begin{bmatrix} \frac{1}{m} & 0 & 0 \\ 0 & \frac{1}{m} & 0 \\ 0 & 0 & \frac{1}{m} \end{bmatrix} \begin{bmatrix} F_u \\ F_v \\ F_N \end{bmatrix} \quad (13)$$

$$\begin{bmatrix} u \\ v \\ r \end{bmatrix} = (B^T)^{-1} \cdot \frac{R}{n} \begin{bmatrix} \omega_{m1} \\ \omega_{m2} \\ \omega_{m3} \end{bmatrix} \quad (14)$$

Figure 22: The Mobile Robot Dynamic Model.

The Actuating unit used four small DC motor and In order to control the direction of the motors, the two right side and two left side motors were connected together with same polarity obtaining a two wheels mobile robot and these two motors were typically connected in series and equally shared the supplied voltage. By using Newton's law, Kirchhoff's law and Ohm's laws, students were able to *mathematically described the models control* of each actuator as illustrated in Fig. 7. where the PID controller was used.

The mathematical model of the control algorithm structure was the most significant step as the control unit had the task to take the robot to the desired position with desired orientation and avoiding the obstacles, along with the gathering and processing input and output data. The control unit model as shown in Fig. 23 has two circuits with the feedback loop. The main feedback loop was used for the robot position control trough the Ultrasonic Sensor (HC SR 04).

Figure 23: The Mobile Robot Control Block diagram.

As the mobile robot mathematical model was performed, students started working in the simulation as shown in Fig. 24, Fig. 25 and Fig. 26. Students built a Simulink model of the DC motors, which the robot was driven by them. From the mathematical model, students have derived the govern equations and the transfer function for the simulation. APID controller were used with $K_p=17$, $K_i=10$, $K_d=7$ and the values of the motors have set as follow, $V_{dc}=12$; $b=0.00003$; $J=0.01$ $K=0.023$; $R=1$; and $L=0.5$;

a. Step Response

b. Impulse Response

d. Bode Diagram.

Figure 24: DC Motor Properties from M. File.

Figure 25: Simulink Model of DC Motor.

Figure 26: Dc Motor with PID Controller Simulink Results.

The wiring diagram was a very essential part in the robot system design process where it used to connect the system software and hardware. The schematic diagram drawing is important in avoiding the problems and faults before it happening during system operation and facilitate the non-engineers the electronic system connections understanding. The wiring diagram was performed by using Frizzing software as shown in Fig. 27.

Figure 27: The Mobile Robot Electronic Circuit.

The robot system sensory unit was two ultrasonic sensors (HC SR 04), [23]. when the robot collides with an obstacle, The Ultrasonic transmitter transmits an ultrasonic wave, when this wave gets objected within 30cm it reflects back, this reflected wave is observed by the Ultrasonic receiver module, which sends a signal to the Arduino Uno microcontroller sending a signal to the L298N motor driver sending a pulse to the motors to change its rotation direction by change the polarity of the motors through the H-Bridge switches as shown above.

Students use the C/C++ languages with Arduino Union microcontroller platform to develop the programming code of the robot system. During the code programming students set the two Ultrasonic Sensors(HC SR 04) distance between the robot and the object up to 30 cm as shown in Fig. 28.

```
//Right Motor Arduino motor Drive
pinMode (RForward, OUTPUT) ;
pinMode (RRevers, OUTPUT) ;
//left Motor Arduino motor Drive
pinMode (LForward, OUTPUT) ;
pinMode (LRevers, OUTPUT) ;
void turnL (void) {
    digitalWrite (RForward, HIGH) ;
    digitalWrite (RRevers, LOW) ;
    digitalWrite (LForward, LOW) ;
    digitalWrite (LRevers, HIGH) ;
}
void turnR (void) {
    digitalWrite (RForward, LOW) ;
    digitalWrite (RRevers, HIGH) ;
    digitalWrite (LForward, HIGH) ;
    digitalWrite (LRevers, LOW) ;
}
void rev (void) {
    digitalWrite (RForward, LOW) ;
    digitalWrite (RRevers, HIGH) ;
    digitalWrite (LForward, LOW) ;
    digitalWrite (LRevers, HIGH) ;
}
void forw (void) {
    digitalWrite (RForward, HIGH) ;
    digitalWrite (RRevers, LOW) ;
    digitalWrite (LForward, HIGH) ;
    digitalWrite (LRevers, LOW) ;
}
```

Figure 28: The Programming Code in Arduino Platform.

The working principle of the project software was developed through the flowchart in Fig. 29. This flowchart gives the summary of the project main function performing, which is the obstacle avoidance, where the robot system has two ultrasonic sensors for sensory unit for supplying the robot position in space.

Figure 29: The System Software Flowchart.

The motors, circuit diagram, sensory unit, electrical components, the programming language and the mobile robot system software flowchart were provided, the students felt free to apply their creativity and skills in the modification and fabrication of the circuit, designing original robots' locomotion systems in a single robotic structure Fig. 30. They also need to troubleshoot the system and tune the circuit parameters to optimize the robot system performance.

Figure 30: The Mobile Robot Platform.

RESULTS AND DISCUSSIONS

Participants and The grade Distribution

A total of 46 students were enrolled on robotics course (802204-3) in spring 2018. All of the students were mechanical engineering students in their junior or senior year. Most of them had hands-on and fabrication experience from prior courses they had taken in the curriculum (35 students, 76%). Typically, there were 35 from fourth year (76%) and 11 from fifth year (23.9%) students.

In Fig. 31, the percentage of students who got A and A+ is 6.52%, the percentage of students who got B and B+ is 17.39%, the percentage of students who got C and C+ is 36.96%, and the percentage of students who got D and D+ is 39.13% and 0% who got F.

Figure 31: Grade Distribution

Attainment of Students Outcomes (SOS)

A Course Evaluation Survey (CES) was handed out to the students at the end of the course for the indirect assessment. Students have confirmed the validation of robotics course (802204-3) objectives and have achieved the Satisfactory-Exemplary levels as shown in Fig. 32. Students responses were analyzed as follows: 25% strongly agreed, 50% agreed, 24% neutral and 1% disagreed, that robotics course 802204-3 facilitated them to apply knowledge of mathematics, science, and engineering an identify, formulate, and solve engineering problems, 50% strongly agreed, 24% agreed, 25% neutral and 1% disagreed, that robotics course (802204-3) provided them with the ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability, as well as, 75% strongly agreed, 15% agreed, 8% neutral and 2% disagreed, that robotics course (802204-3) developed their ability to communicate effectively, Also, 50% strongly agreed, 25% agreed, 23% neutral and 2% disagreed, that the robotics course (802204-3) helped them understanding of professional and ethical responsibility the broad education and understand the impact of engineering solutions in a global, economic, environmental, and societal context and a knowledge of contemporary issues, 25% agreed, 25% agreed, 50% neutral, that robotics course (802204-3) improved their ability to function on multidisciplinary teams, 25% agreed, 50% agreed, 25% neutral, that robotics course (802204-3) ensured them with the ability to design and conduct experiments, as well as to analyze and interpret data, and 50% agreed, 25% agreed, 50% neutral, that robotics course (802204-3) provided them with the recognition of the need for, and the ability to engage in life-long learning.

Figure 23: Students Outcomes (SOS) Survey.

Problems and Difficulties Encountered in Robotic PBL Curriculum

During the PBL process including design, implement, operate, and observe activities in labs. Students faced several problems. To Achieve a robotic projects in Fig.18 and Fig. 33, students had to apply and acquired the hands-on, soft and hard skills to build, model, control subsystems, and install each wiring circuit, and integrate them with Arduino and MATLAB software platforms into the physical system to enable the robot to execute its main function. As seen in Fig. 31, most of the reported problems were related to the domain knowledge of prior courses in the curriculum and robotics concepts, including the Projects ideas selection (13.04%), mechanism structure design (17.39%), debugging (10.87%), circuit design (10.87%), the whole system integration (19.56%), and purchasing the required components (8.69%). As for the project itself, some skills related to the work were asked to be developed such as teamwork (10.87%) and open-discussions (8.69%) where observed as the most difficult issues.

However, the students attribute the difficulty of developing sufficient domain knowledge and skills to internal factors, such as a deficiency of experience (19.56%) and proficiency (17.39%), and external factors, such as budget (13.04), prior courses outcomes (10.87), and instruments (10.87). The findings suggested that students with this type of problems were more active learners and were more likely to view the problems as challenges that could be succeed in dealing with.

Figure 33: The Reported Challenging Problems and Difficulties Through The Projects.

CONCLUSIONS

The PBL approach was implemented successfully to teach the robotics course(802204-3) in the MEP at TU. The content and instruction of the PBL promoted student experiences and performances in the learning of robotics practice and theory. It also was noticed, it gave the student the confidence to solve real problems in the local community in the future.

Despite the student shortage of experiences that challenged and inhibited students' progress, they were permanently encouraged and excited by robot projects and would engage to complete the project. In contrast to the students' previous learning experiences with Machine Design, system design and control, electronic appeared to be more motivating and therefore exciting to go through the projects.

During the project work and laboratory sessions, was observed that the PBL encouraged students to discuss the robotics subjects and the projects' developing progress frequently, where student teams had to hold regular meetings to share and extend their experience in developing the project. This discussion with each other and with the instructor enabled them to teach each other and strengthen and improved their understanding of the robotics concepts and provides them with hands-on experience and knowledge that are not usually presented in the textbook. Also, the teamwork was observed and regarded generally to be more sufficient in terms of active-learning and to be more interesting than individual work. The evaluations also suggested that students appreciated the robotics projects as an aesthetic engineering artifact that combined we believe that the designed and implemented projects can be improved by the students to be patented and commercialize or extend students motivations towards the further robotics researches with provided supplement of courage and guidance.

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