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Design and Development of a Cartesian Robot for Multi-disciplinary Engineering Education*

SELÇUK MISTIKOGLU and IBRAHIM ÖZYALÇIN
Mustafa Kemal University, Faculty of Engineering, Department of Mechanical Engineering, Iskenderun Campus, 31200 Iskenderun, Hatay, Turkey. E-mail: selcukmistikoglu@gmail.com

This paper presents a teaching approach based on hands-on learning. The details of the approach presented here cover the theoretical aspects and the practical implementation of the engineering study. The study provides details of a model for a multi-disciplinary engineering education approach that provides the students with fundamental theoretical and practical knowledge. Furthermore, the results of the study reveal that the method is in compliance with the Accreditation Board for Engineering and Technology (ABET) criteria for education in engineering. Moreover, the benefits of the approach and the related results, which indicate that graduating students do benefit from the education provided, are also presented.

Keywords: cartesian robot design; engineering education; multi-disciplinary study; project based learning; accreditations criteria

1. INTRODUCTION

THE ISSUE OF ENGINEERING EDUCATION has attracted much attention in the past and the related literature provides some clear educational guidelines for each specific discipline. This is because most disciplines, apart from a few that have emerged in the last few decades, had their foundations laid early in the last century. From the literature it seems that it is the integration of the new disciplines with relatively older ones that appears to dominate the educational discussions. Most institutions have developed so-called interdisciplinary engineering education by combining the courses in their own way. Some studies of interdisciplinary engineering education [1, 2] reveal that the outline of the proposed curriculum is a result of the review of the specific institution, which is mainly defined by the available facilities, academic staff, economic issues [3] and so on. Therefore, the curriculum developed is related to the resources and facilities of a specific institution more than anything else.

This study proposes a teaching method that is based on project and research-oriented learning. Although the method focuses mainly on post-graduate engineering education, it is also applied to undergraduate engineering education. The only shortcoming of the method for undergraduate engineering education is that the student is expected to play an active role in the learning and research stages of the study. This may not be an issue in post-graduate education. In addition, this approach puts unnecessary pressure on undergraduate students; therefore it may be beneficial to split the students into groups so that the load is shared between them. The teamwork [4] approach would also provide necessary setting for students to experience a real-life working environment on a controlled and supervised platform [5, 6]. The interdisciplinary engineering teaching approach also complies with the Accreditation Board for Engineering and Technology (ABET) criteria [4], details of which will be provided later.

Having defined the outline of the approach, another main issue is the definition of the topic for study. In determining the topics, one should pay attention to detail so that the topic involves all the necessary disciplines at the required content and level.

To be more specific, a typical topic is required to involve mechanical engineering, electrical engineering, electronics engineering, computer science engineering and related areas. This field of study is commonly considered as the area of mechatronics, where all these topics and related systems are not only grouped together but are also integrated in a synergetic manner. Robotic systems are among the most widely accepted mechatronic systems.

Robotic manipulator systems are mainly categorized as being of either parallel or serial types. The difference is that in parallel types each axis operates independently, whereas in serial systems the performance of preceding units depends on the subsequent ones, as in articulated arms. To allow step-wise design, integration and testing procedures, the study favours a parallel type manipulator. The advantage of using a parallel type is that

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the engineering student can easily observe the development stages by himself or herself having successful operated the independent operation of each unit or axis. This in turn aids the assessment and progress of the work as the sub-stages of the development can be achieved and the developed system can be tested against design criteria and performance. On the other hand, a typical serial system would require the installation of all sub-systems to perform the expected function since the performance of each unit depends on the performance of the preceding ones. Hence, the present study favours the parallel type manipulator. The project-based and research-oriented engineering education model proposed is implemented through the design and development of a high speed [7] robotic system.

2. BRIEF DESCRIPTION OF A CARTESIAN TYPE PARALLEL MANIPULATOR

The capacity of a typical Cartesian type parallel manipulator is defined by the extent of the axes of the robot, which determines the working area/volume or working envelope. The degrees-of-freedom (DOF) of a robot is defined by the number of independent motion capabilities of its mechanical parts achieved in the form of translational and rotational motion [1]. An important feature of the parallel type Cartesian robot systems is that they operate at high speed and precision. In addition, they generate very low levels of vibration during operation. These properties of Cartesian robots make such systems very suitable for high speed and high precision industrial applications [4]. The favoured parallel manipulator possesses three DOF achieved by translation on the x, y and z axes. The limited number of DOF makes this robotic system cost-effective, robust and easily controllable. In recent years, a common trend has been towards the design and development of systems that reduce the dependency of motion modes on each other, thereby improving the overall performance of the system. The very basic outcome of the trend is that it simply eases the design, manufacture and installation stages of the development as well as the performance of test procedures [8–17].

The overall system structure and the robot arm layout are illustrated in Fig. 1. As seen from the figure, the system consists of a main fixed frame that accommodates the arms. Each arm operates on an independent axis. Considering that each arm possesses two DOFs, the expected number of DOF of the system is six. However, this number is reduced to three as each arm also restricts one DOF of the system during their installation as a result of assembly conditions and joint properties. Thus, the overall DOF of the system is three. In other words, the system motion properties resemble a typical Cartesian robot that consists of three independently driven platforms providing three DOF.

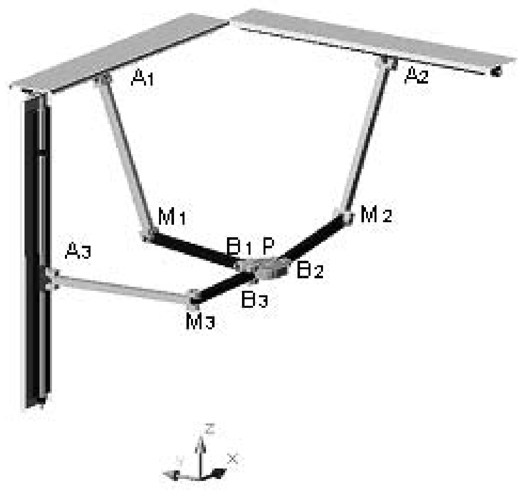

Fig. 1. Cartesian robot system, overall system structure and arm layout [18].

The robot consists of three arms operated independently. Each arm uses one prismatic and three revolute joints to form the PRRR joint set [18]. These arms support a platform that stands in the centre of the system structure. The points B_1, B_2 and B_3 seen in Fig. 1 represent joint points of the platform. The fixed body of the system provides the sliding joints at points A_1, A_2 and A_3 for these arms. Each arm has two elements that join at M_i ($i = 1, 2, 3$), and the point P represents the midpoint of the platform.

3. THE PROPOSED TEACHING METHOD BASED ON PROJECT AND RESEARCH-ORIENTED LEARNING

The objective of the proposed method is to give the students the skills for interdisciplinary thinking and understanding systems. It also provides details of the design of interdisciplinary systems. These provide the students with the necessary tools to cross disciplinary boundaries so that their view of a system is not limited or restricted in any way. About a few decades ago, engineering education used to be considered slightly differently from nowadays. The main difference was in the way in which educational matters and teaching were handled. The current trend is towards providing students with an interdisciplinary view and knowledge, so allowing them to see the world from different engineering discipline perspectives. This way of thinking is most beneficial where a complex interdisciplinary system is to be developed by a team of engineers. An engineer's ability to view an issue in a similar way to a colleague improves communication, provides better understanding of the system between all team members and, all in all, reduces the completion period of the overall project while improving the quality and functionality of the system. Thus, it is an ideal tool for all engineers, whatever their discipline. A mechatronics engineer's views [1, 19] are good examples of interdisciplinary engineering views.

4. CROSSING THE BOUNDARIES OF ENGINEERING DISCIPLINES

One of the skills that is vitally important for an engineering student is the ability to cross interdisciplinary boundaries. As this suggests, the idea behind this approach is to provide the student with an interdisciplinary point of view and the necessary skills so that any design issue is not strictly considered in a specific discipline but looked at in total. Achievement of such a skill is only possible by providing the student with the necessary teaching to have the necessary background to accomplish such a task, supported by training through project-based studies similar to those proposed in this paper.

The design and development of most 21st century products appears to involve multi-disciplinary efforts [20]. An interesting point is that most novel products bear multi-functional, compact and cost effective features that are the direct result of successful interdisciplinary team work. Typically, such a system would have a highly sophisticated user interface, a computing unit with varying power levels, sometimes an actuator with complex behaviours, but mainly a complex overall mechanical system with a complex geometry developed by using solid modelling technology. It is worth noting that such systems have been constantly improving as these interdisciplinary design tools provide more and more engineers with a better view of products, design and development issues [21].

There are a few critical issues in the design and development of an interdisciplinary system:

1. identifying the needs of the customer and clearly defining the outline of the product;
2. writing down the engineering definition of the need, based on customer requirements within the defined outline;
3. clarification of the need and related functions that allow achievement of the functions;
4. design of the system in the functional domain [22];
5. functional analysis and optimization of the system in the functional domain;
6. providing the functions with the necessary means to achieve such functions while considering the effect of choice of a means [23] for the overall system;
7. upon completion of the means providing stage, the system is then studied at level of components, where each means is converted into a component with specific properties.

The above list does not claim to describe the full design process but covers the most important stages that actually shape the design. Each stage contributes to the overall performance of the system as well as its functionality and integrability. In particular, stages 4, 5 and 6 are very important as they are achieved in a multi-disciplinary domain. The advantage of the achievement of a design process in a multi-disciplinary domain is that it mostly results in novel products that are very different from their predecessors. The differences are mostly in terms of cost, functionality, performance, compactness and a highly sophisticated user interface.

To achieve the design process described above, a typical engineering student studying in a multi-disciplinary system development is expected to understand the disciplines involved in the design process of the product. The understanding of such disciplines includes both the theory and the practice [24] of the discipline, or at least the topics related to the design of the product. The question is that a typical engineering student specializes in a discipline and learns some other related subjects superficially. The optimum case for a multi-disciplinary engineer is not to gain expertise in all areas but to have the necessary background in all of them. The necessary level of background is not knowing a specific theory in depth but understanding the actual logic or thinking underlying it and the related theory at very basic level. The main concern of the teaching model proposed in this paper is to teach and train a student so that he or she can gain a self-learning approach.

Similar approaches including some practical differences are reported by Ollis [2], Kurfess [25[and Levin *et al.* [26]. The differences in their approaches are in the project topics that define the content of the teaching. However, the common concept is that all of these approaches are aimed for designing and developing interdisciplinary, namely mechatronics, systems. This is mainly a result of the ABET/EC 2000 criteria, which includes the statement that every graduating student should have a multi-disciplinary experience during his or her undergraduate education. It is clear that one of the best ways of achieving such an experience is to get involved in an interdisciplinary project-based learning programme. The paper by Ollis [2] provides the details of a number of universities and their project-based learning approaches.

5. THE STAGES OF DESIGN AND DEVELOPMENT OF THE SYSTEM

The first stage of the design method proposed is to identify the need for the system [27]. For this study, a robust robotic system that can achieve 3D motion (translational motion in the x, y and z axes) to perform industrial tasks such as sheet metal cutting, assembling, drilling, welding and so on is needed. Therefore, the basic need can be defined as a system that achieves high precision machining based on the 3D translational motion of a tool

Fig. 2. Overall system structure.

platform The inputs to the system are task definition and power (most likely in electrical form). The output from the system is the desired motion.

As the block diagram of the system in Fig. 2 illustrates, the system has two inputs and one output. The inputs are Task Description and Power, while the output is Motion in 3D. As mentioned earlier, the type of robot chosen is a parallel type Cartesian one, the operation of which is based on arms and a moving platform. Therefore, the main function of the system is to convert the task settings to prescribed motions in 3D using the power provided as input [28].

Figure 3 gives a detailed block diagram of the system. The system is expected to operate on receipt of the task description. The custom-made software used for this purpose receives the task description and generates the commands defining the axial timed motions. These settings are then received by the controllers that drive the actuators, thus generating the desired motion. During this operation, the motion of each axis is sensed and the controller gets the feedback of the results for performance analysis. The analysis results are then displayed on the user interface module. The outline of the robotic system to be designed was divided into three main units: mechanical, electrical and computing. The user interface unit is considered to be a part of the computing system where the custom-made software and related hardware resides. The motor drives and sensors as well as the actuators are considered to be the electrical unit of the system. The mechanical parts of the system consist of the main frame, the arms and so on.

The design and development stages of the proposed Cartesian robot consist of the following stages, which are achieved in a parallel manner or simultaneously:

- the design and development of the mechanical system;
- the design and development of the electronic system;
- the design and development of the software system.

The idea behind the parallel or simultaneous workings is to ensure the compatibility of the subsystems listed above as well as to ensure that the overall system performance is improved through synergetic integration. The objective of the teaching approach is to provide the student with the necessary skills to allow him or her to develop such a system. The approach aims not at putting the above-mentioned systems together but at integrating them. If they are to be integrated then they need to be designed to fit together. If they are to be designed to fit together, then the design of each module is required to take the interface-related details of the others into account. The idea behind the integration of systems is to form more synergetic systems. In other words, the overall system performance is expected to be better than the performance of sub-systems. This requires design of such systems at abstract levels where the design issues are handled at functional levels where no hardware or software properties are considered. At this level, the design takes a function-oriented form [29]. In this design approach, the system starts at the most abstract level and finishes at the level of the detailed components. Because the systems-related design studies and integration procedures are all defined at functional level, the overall task of system integration and performance tests becomes far easier. In addition, the failure related loop-backs are reduced. A typical means for the above defined functions are those illustrated in Fig. 4. As the figure illustrates, the functions are provided with the actual means although the components are yet to be defined in terms of physical properties such as dimension or power levels, and so on.

Figure 4 shows the motion achieved by the axial mechanism, which combines the axial motions along the x, y and z axes. However, the mechanism also allows individual axial motion, which is the natural result of the type of robot chosen. The advantage of selecting this type of robot is that it also facilitates the independent development and

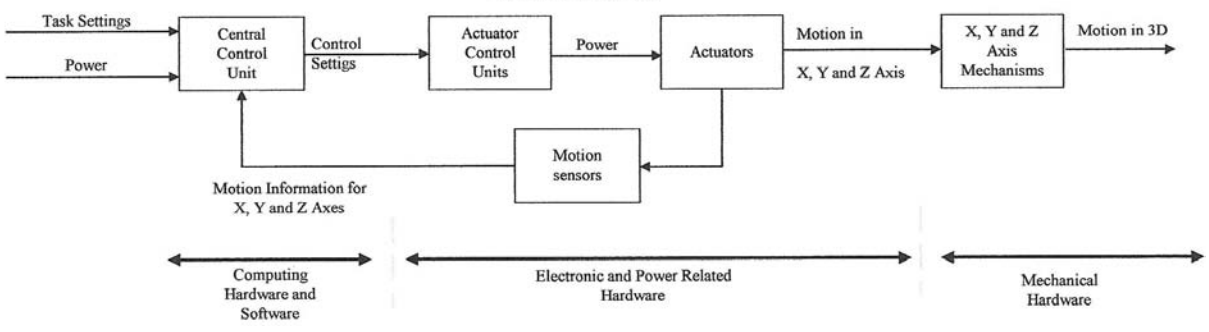

Fig. 3. Detailed functional block diagram of the system.

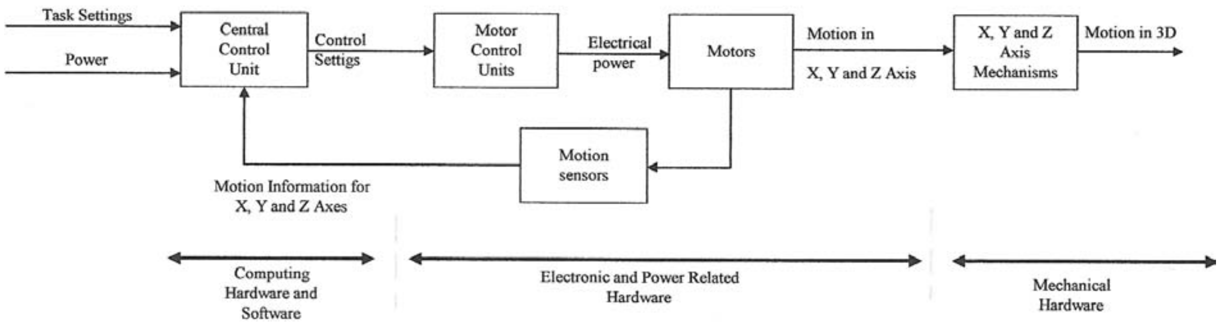

Fig. 4. The means provided for the functions.

testing of arm modules. This also leads to a parallel development of the arm modules, where common units such as motor controllers are designed to meet the requirements of all arm types, while mechanical designs diverge as each arm module operates on a different axis with its own operational principles. The design and development stages of the robotic system can then be categorized as:

1. the design and development of common axial motion unit parts;
2. the design and development of specific axial motion unit parts;
3. the integration of axial motion unit parts to form the arms;
4. the integration of arms to the fixed body;
5. the integration of motor controller units of axial motion unit part to main controller;
6. the integration of sensors for feedback control.

In Table 1, the main mechanical components and related system elements are analysed and the system elements listed are provided with the means to perform the functions. The table provides details of the components in terms of their physical, motion-related properties, their adjustable parts and their contribution to the overall performance of the system. The last column of the table presents the origin of the components: either custom-made or off-the-shelf.

6. SYSTEMS INTEGRATION AND PERFORMANCE TESTS FOR THE DEVELOPED ROBOT

Figure 5 shows the robotic system.

As the focus of this paper is on engineering education, only the sections that are relevant to the discussion on the teaching approach in the design and development stages of the robotic system have been presented briefly. Below we provide details of the testing procedure, the technical difficulties experienced, the analysis of the problem and the statement of the solution and details related.

Table 1. Properties and related analysis of system components

System component	Physical properties	Motion related properties	Adjustable parts	Contribution to the overall performance of the system	Origin
Main frame	Solid, stable, high mass	Fixed to ground	Foots for levelling	Due to high mass minimizing vibrations transmitted to ground	Custom made
Arm mechanisms	Light weight alloys, low friction bearings	Highly accurate motion. No backlash	No adjustable parts	Highly accurate positioner; High repeatability	Custom made
Motors	Electrically activated, High torque, suitable for position control	Accurately positioned	Speed and torque output	Precise positioning	Off-the-shelf
Motor control cards	High load protected	Suitable for accurate positioning	Voltage and current output	Precise positioning	Custom made
Linear transmission	Low friction	Converts rotational motion into linear motion	—	Smooth motion	Custom made
Motor control software	—	Identification of axial motions	All motion related parameters	Smoothness; Synchronization of the actual task	Custom made

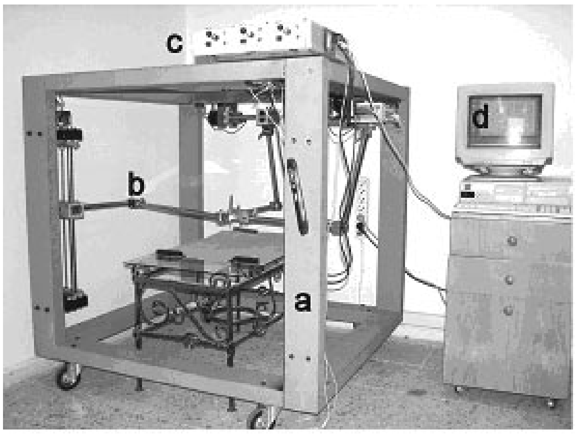

Fig. 5. The Cartesian robot system developed [28]: (a) fixed main frame, (b) moving arms, (c) controller module and (d) PC for execution of the control software.

The testing procedure is as follows:

- STAGE I: Testing the system in each axis independently
- STAGE II: Testing a combination of sequential motions in two axes
- STAGE III: Testing a combination of simultaneous motions in two axes
- STAGE IV: Testing simultaneous motions in three dimensions

The details of the test procedures, the technical problems experienced, the solutions proposed and the results achieved are presented in Table 2.

6.1. Stage I Tests

During this test, each axial motion is tested for performance criteria. The observed technical problems were vibration and noise from the mechanical system, especially from the transmission and actuation units. It was also noted that the motors draw too much current at start up. After noting these issues, the student analysed the problem and identified the cause as a misformed control signal from the controller unit. After a few trial and error attempts, the solutions proposed by the students were to modify the control signal generation format in the software, to add a low-pass filter in the motor control card hardware and a flexible joint in the mechanical transmission unit. Any of these suggested solutions individually provides an answer to the problem. The experimental study was productive for the students as it allowed them to see the problems from a number of different engineering perspectives and to provide solution for each. However, it is surprising that the actual implemented solution simply employs all of them. The idea, offered by the students, is to ensure flexible coupling between the software and the mechanical platform.

Table 2. Test stages and achieved results (SW*. Software, EHW*. Electronic hardware, MHW*. Mechanical hardware)

Test stage	Technical problem experienced	Problem analysis and solution description		Multi-disciplinary solution			Results
		Cause identified	**Solution suggested**	**SW***	**EHW***	**MHW***	
STAGE I Motion test on individual axis	Noise and vibration during achievement of motion, motors drawing high currents, driver boards overheating	Discrete or intermittent nature of the control signal from PC	1) Implementation of rate of change in control signal generation	√	—	—	i) Reduced vibration ii) Limited driver board current iii) Reduced noise iv) Smooth operation
			2) Electronic low-pass filtering	—	√	—	
STAGE II Motion test for square like shape	No problem is experienced	—	—	—	—	—	—
STAGE III Motion test for circle	Non-synchronized, sequential motion resulting in accurate positioning	Slow communication	Increased baud-rate	√	√	—	i) Smoother operation ii) Simultaneous achievement of axial motion iii) Better positioning
		Sequential activation	Separate, parallel port activation signal	√	√	—	
STAGE IV Motion test in metal cutting	Varying tool mass resulting in varying positioning performance	Mechanical activation	Implementation of worm-gear	√	√	√	i) Smoother operation in z-axis ii) Faster z-axis motor iii) Higher performance in positioning
		Low power output from z-axis motor	New motor	√	√	√	

6.2. Stage II Tests

No technical difficulties or problems were experienced in this set of tests. Therefore, in this stage learning was limited to practising the activation of more than two axial motions achieved in a sequential manner. The results of the tests have shown that the square path was followed successfully.

6.3. Stage III Tests

These tests performed for controlling synchronized motion reveal that drifting is still an issue. In order to improve the performance of the system, the communication speed for the control settings transfer rate (boud rate) has been increased and the relevant hardware has been modified accordingly. In addition, the activation signal for axial motion generation has been transferred from serial communication to parallel, providing more resources for serial communication and the transfer of control settings. In addition, providing a parallel activation signal for all the axes at once improves the performance, which previously had been partly degraded by the sequential activation of the motor controllers. During these tests, the student experienced some technical difficulties and, after analysis of the problem and identification of the issue causing the problem, the solution was proposed and implemented. The results of the implemented solution have indicated that the drift from the defined path has been reduced to acceptable levels. The results of this test have shown that a circular task path is achieved with acceptably tolerable levels (±2.5 mm drift).

6.4. Stage IV Tests

The last stage of the tests involved the actual implementation of an industrial task, i.e. the metal cutting process. The process requires the integration of a cutting tool with the application platform. After fixing the sheet metal and operating the cutter, the robot is activated and, after a successful cutting process, the metal sheet was cut as defined in the task description. Figure 6 illustrates the actual cutting in action (left) and shows the results of the cutting process (right). As seen from the figure, apart from the starting point, which students later noticed, the cutting process is considered to be successfully implemented.

7. PEDAGOGICAL ASSESSMENT

The proposed engineering approach has been used on both a group of post-graduate students and on 4th-year undergraduate mechanical engineering students. The outcome of the approach has been discussed above in detail for post-graduate students. The results of the approach for undergraduate students are given in Table 3. Because the number of post-graduate students is not sufficiently large, the related assessment in this case is based mostly on supervision-based observation, as presented in the relevant section.

Fig. 6. Implementation of the actual industrial application of metal sheet cutting [28].

Table 3. The learning outcomes of the pedagogical assessment for undergraduate study

Initial capabilities	**Required skills. Design and development of:**	**Technological and practical support provided on:**	**Gained skills. Ability to design and develop or perform:**
Mechanics and material science	mechatronics systems	electronic engineering	an electro-mechanical system
Computer-aided design	control and instrumentation	system modelling, control and simulation studies	a control system and instrumentation
Computer-aided manufacturing	real-time systems	automation, control and instrumentation	functional analysis and fault diagnosis
System dynamics and modelling	sensors and sensory systems	interdisciplinary project based learning	systems integration

Table 4. Outcome of the questionnaire results and issues investigated

	Overall assessment of gains	
Issues analysed in the questionnaire	**Number of students**	**Success in achieving the task (%)**
Information transfer	18	91
Comprehension	16	83
Improvement in practical skills	18	94

The results presented in Table 3 provide details of the pedagogical assessment of the undergraduate study. The first column provides details about the initial capabilities of students at the beginning of the courses. The information presented confirms the general state of a typical mechanical engineering student with a typical background of mainly mechanical engineering subjects. The second column provides the required skills, mainly focusing on mechatronics systems-related design and development abilities. These also include control, real-time system and sensory systems and so on. The courses considered in this study provide the students with the ability to design, develop and manufacture, and for system integration and implementation of interdisciplinary systems. The students are also provided with the analysis for design of systems that enable functional analysis of systems. The functional analysis then leads to successful application of fault diagnosis studies.

Considering the results presented in Table 3, it is clear that a typical 3rd year student taking a few courses introduces himself or herself to a new study area and benefits from the project-based learning proposed in the paper. The questionnaire results for the undergraduate student group are listed in Table 4. The outcome of the questionnaire shows the results and issues investigated from the responses from the students taking the courses (one course each term). Nineteen students took the courses.

8. VALIDATION OF THE TEACHING APPROACH AND DISCUSSION OF RESULTS

According to ABET, a typical engineering education is required to meet certain criteria for accreditation. The criteria are as follows:

Outcome a: an ability to apply knowledge of mathematics, science, and engineering
Outcome b: an ability to design and conduct experiments, as well as to analyse and interpret data
Outcome c: an ability to design a system, component, or process to meet desired needs
Outcome d: an ability to function in multi-disciplinary teams
Outcome e: an ability to identify, formulate, and solve engineering problems
Outcome f: an understanding of professional and ethical responsibility
Outcome g: an ability to communicate effectively
Outcome h: the broad education necessary to understand the impact of engineering solutions in a global and societal context
Outcome i: a recognition of the need for, and the ability to engage in, life-long learning
Outcome j: a knowledge of contemporary issues
Outcome k: an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

Considering that the approach proposed aims at providing the student with the necessary multi-disciplinary background and the opportunity to implement the knowledge to gain practical experience, it does meet the criteria of **a** and **b**. As the actual teaching method is oriented to the design process, criteria **c, d** and **g** are also met. The performance tests and related studies presented do meet criteria **e**, **f**, **h**, **i** and **k**. The criteria of **j** is more general in the sense that it does require the consideration of design issues in a broader context than actual customer needs. Therefore, this issue needs to be addressed for design cases where the product has global effects.

9. CONCLUSIONS

The teaching method proposed in this study is a theory-based practice-supported one that consists of basic training and project-based hands-on learning type engineering education. The advantage of the method proposed is that it provides the students with the real-life working environments where they experience a teamwork environment, have a chance to practise their theoretical knowledge and also see the real-life engineering problems. Above all, they learn how to deal with such situations. Actual implementation of the solutions suggested by the student themselves makes them recognize that learning is a continuous process dictated by weaknesses in their background related to the work they conduct. More importantly, they take responsibility for their decisions and actions during such project-based studies. Hence, they gain more experience and maturity before they actually graduate and start working in a real workplace. Considering these points, it would not be wrong to state that the proposed approach does meet the ABET criteria, although only a few institutions have actually made successful accreditation applications.

The results of the pedagogical assessment presented above show that the proposed approach does contribute to students' engineering education. The main contribution of the approach for engineering students is that they gain a broader view of the technical problems. This enhanced view provides the students with the ability to cope with and provide solutions to interdisciplinary technical problems. These results are in line with the findings presented in [2, 25, 26]. It can be concluded that the project-based hands-on learning type engineering education approach provides engineering students with the necessary theoretical multi-disciplinary background, allows the transfer of related theory into practice, improves their teamwork skills, contributes to their research skills and self-learning capabilities and thus provides them with the ability to design and develop multi-disciplinary systems.

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Selçuk Mistikoglu received his degree in Mechanical Engineering in 1983 from Anadolu University. In 1987 and 1995, he received his M.Sc. and Ph.D. degrees, respectively, from Çukurova University, Adana. He has worked in the Mechanical Engineering Department of Mustafa Kemal University, Turkey since 1995. He took part in and/or has led the Turkish Higher Education Council/World Bank Industrial Education Project Curriculum in curriculum development projects for Mechanical Engineering Groups in 1996, 1997 and 2002.

Ibrahim Özyalçin graduated from Trakya University engineering department in 1988. Soon after graduation he started working as an instructor at Mustafa Kemal University, Iskenderun Higher Technical Vocational School. He was awarded an MSc degree in 2006. He is currently working at Mustafa Kemal University, Iskenderun Higher Technical Vocational School as an instructor.