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Evaluation of the TPACK Framework for Instructing a Lesson in the Mechatronics Course

Dr. S M Mizanoor Rahman, The Pennsylvania State University

Dr. Mizanoor Rahman is an assistant professor of mechanical engineering at The Pennsylvania State University, Scranton. His research interests include collaborative robotics, human-robot interaction, electro-mechanical design, assistive and rehabilitation robotics, ergonomics and STEM education.

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Abstract

In this paper, the Technological, Pedagogical and Content Knowledge (TPACK) instructional framework was developed, implemented and evaluated for instructing a topic of the mechatronics course to senior students in mechanical engineering major. To do so, a topic (introduction to a robotic manipulation system) of the mechatronics course was selected to be instructed to the students in a regular classroom setting following the TPACK framework. The instructor developed the lesson aligning with the TPACK framework and then instructed the lesson to 9 senior mechanical engineering students in the classroom plus lab setting. An evaluation team consisting of 6 engineering students (3 senior students and 3 graduate students) observed the instructor's instruction and evaluated the instructional quality as well as the instructional outcomes following an evaluation scheme. Then, the instructor instructed the same lesson to another group of senior mechanical engineering students (9 in number) in the same classroom setting following the traditional (ordinary) instructional approach (preparation of the lesson did not align with the TPACK framework), and the same evaluation team evaluated the instructional quality and instructional outcomes. Then, the independent evaluation results between the TPACK-based instruction and the traditional instruction were compared. The results showed that the instructional quality and instructional outcomes obtained for the TPACK framework were significantly better than that for the traditional instructional approach. Then, the prospects, challenges and burdens that instructors might face for designing and implementing the TPACK framework were investigated and necessary training and institutional support for instructors were determined. The results can be used as a working model of the TPACK framework. The results can inspire and guide instruction design for STEM courses, especially engineering and technology courses following the TPACK framework.

1. Introduction

1.1 Background and motivation

As new technologies are coming, some technologies are also being used for pedagogical purposes. It is expected that applications of advanced technologies such as AI (artificial intelligence) may significantly improve pedagogies and instructional performance, which may directly impact instructional outcomes [1]. This is why educators are required to gain knowledge and skills in using educational technologies. However, technologies used in education and instruction cannot be adopted as standalone facilities. It seems to be necessary to identify its correlations with subject matters, pedagogical strategies, educational objectives, educators' personalities, learners' mentality and behaviors, facilities and environment provided by educational institutions, etc. [1]. Considering this interrelationship between educational technologies and other educational aspects, the technological-pedagogical and content knowledge (TPACK) framework has been developed [2]-[4]. The main objective of the TPACK framework is to determine the correlation between educational technologies and other educational aspects, analyze the relationship, help educators prepare themselves on the relationship so that they can educate learners aligning with the relationship [5]. Under the TPACK framework, an instructor needs to gain knowledge and skills in the subject matter (content knowledge), learn appropriate pedagogies to teach the subject matter to learners, gain expertise in educational technologies to incorporate them into the pedagogies, and understand the relationships among these three complementary knowledge domains (subject matter or content knowledge, pedagogical knowledge and technological knowledge). Intersections of these three foundational knowledge domains of the TPACK framework have constituted four additional knowledge subdomains such as the technological pedagogical knowledge (TPK), pedagogical content knowledge (PCK), technological content knowledge (TCK) and the entire technological pedagogical and content knowledge (TPACK) [2]-[5].

It is expected that alignment with the TPACK framework can result in instructional outcomes, which cannot be achieved if educational technologies, pedagogies and subject matter knowledge are considered separately [2]-[5]. As the literature shows, in addition to improving subject matter learning, the application of TPACK to instruction design can increase the socioemotional abilities of students such as interest, motivation, engagement in learning, etc. [6]-[7]. Nonetheless, the TPACK framework remains a theoretical framework, its applications in developing and implementing lessons in actual classroom settings have not been investigated adequately. A few preliminary initiatives with the TPACK framework are available, but these are limited to K-12 STEM instruction, and these are also not verified adequately in actual classroom environments [6]-[8]. Successful applications of TPACK framework in instructional design of college level STEM lessons are usually not reported in the literature. It is challenging to teach mechatronics in college level education. It is realized that application of the TPACK framework in instruction design may make instructors more prepared to instruct topics in the mechatronics course. However, application of the TPACK framework to instruct students for mechatronics and similar courses has not received much attention [3]. Recently, an initiative was taken to instruct mechatronics topics following the TPACK approach [25]. However, the initiative needed substantial evaluations addressing its challenges and burdens, generalizability and possibility of generating misconceptions and misrepresentations. This paper aims to address these limitations.

1.2 Objectives

Being motivated by the above background information, to address the gaps in the literature, the objectives of this paper were to design the instruction of a topic in the mechatronics course following the TPACK framework, implement the lesson in an actual classroom setting, evaluate the instructional outcomes by independent observers and compare the evaluation results with that obtained when the instruction design and implementation was made following the traditional (ordinary) instructional approach (the instruction design did not follow the TPACK framework). The expectation was that the comparative results would demonstrate advantages in instructional outcomes for the TPACK framework, and the results would be used as a working model of the TPACK framework.

1.3 Organization

The rest of paper was organized in the following way: Section 2 analyzes TPACK theories and concepts. Section 3 analyzes state-of-the-art related work. Section 4 presents the materials and methods of the research. This section introduces the participants selected to participate in the studies, the lessons developed for the instruction, the developed pedagogical approaches aligning with the TPACK framework, illustrations of the selected mechatronics topic (the robotic manipulation system), research design, research procedures, and research results and analyses. Section 5 discusses various critical issues related to the research in the application of the TPACK framework. Section 6 presents conclusions and the future research work in this research direction. Then, the acknowledgement, references and appendices are presented.

2. TPACK Theories and Concepts

The phrase 'Content knowledge (CK)' means "a thorough grounding in college-level subject matter" or "command of the subject" (American Council on Education, 1999). CK may also mean the knowledge or understanding of theories, concepts, ways of developing or gaining knowledge, etc. [9]-[10], e.g., the knowledge of an instructor regarding how a robotic system works. The phrase 'Pedagogical knowledge (PK)' means the knowledge about how learners learn, approaches and strategies of teaching, teaching assessment methods, learning theories and philosophies, etc. [9]-[10]. The phrase 'Technological knowledge (TK)' means the knowledge and expertise regarding how educational technologies are used in instructing lessons. The technologies may be digital technologies (e.g., computers, calculators), internet networks, audiovisual systems such as multi-media projectors, software packages, equipment used for experiments and demonstrations, etc. [9]-[10].

The phrase 'Pedagogical content knowledge (PCK)' is a subdomain of the TPACK framework, which shows the knowledge of an instructor about how they combine pedagogy and subject matter appropriately. PCK means how effectively an instructor decides the pedagogy for teaching a specific subject matter [9]-[10]. The phrase 'Technological content knowledge (TCK)' means the knowledge and understanding of an instructor that guides them to decide appropriate technologies to teach a specific subject matter [9]-[10]. The phrase 'Technological pedagogical knowledge (TPK)' means the knowledge and expertise of an instructor that can guide them to decide appropriate technologies to be combined with planned pedagogies [9]-[10].

3. Analysis of Related Work

The literature shows growing interest in TPACK research. The foundational and fundamental knowledge and concepts of the TPACK framework were shared by Mishra and Koehler [2]. Ferdig highlighted the importance of the TPACK framework and provided insights into how technologies could be incorporated into the framework successfully [3]. Mishra and Koehler also provided insights into how technologies could be incorporated into the framework successfully and discussed the problems that an instructor might experience when incorporating technologies into pedagogies [4]. Schmidt et al. contributed to the development of assessment instrument for assessing the TPACK framework to be applied to preservice teacher education [5]. Robotics was introduced as pedagogical technology of the TPACK framework, and it was investigated how robotics-enabled instructions of STEM lessons in middle schools under the TPACK framework impacted STEM teaching and learning [6]-[8].

The literature also shows active research agenda in the field of mechatronics course design and instruction [11]. Simulation-based mechatronics teaching was reported in [12]. A set of new mechatronics education initiatives were taken in [13]. Modular curriculum development for mechatronics technicians was proposed in [14]. In [15], the authors proposed mechatronics curriculum for the university. They focused on language-neutral teaching approach for mechatronics, and the application of low-cost technology for demonstrating mechatronics topics. A two-level project-based mechatronics teaching approach was proposed in [16]. In [17], methods of infusing mechatronics into robotics were proposed to teach mechatronics. In [18], the authors proposed problem-based teaching and learning approaches for the mechatronics course. Virtual reality-based mechatronics instruction was proposed in [19]. An innovative project-based teaching and learning approach was proposed to teach mechatronics in [20]. In [21], the authors proposed insightful approaches to teach mechatronics topics to senior mechanical engineering students. In [22], the authors suggested mechatronics teaching approaches that focused on multidisciplinary learning to meet industry needs. The agile methods for mechatronics teaching were proposed in [23]. The authors proposed a versatile platform to teach mechatronics in [24]. TPACK-based instruction of mechatronics topics was initially proposed in [25].

4. Resources and Methods

4.1 Participants: students and evaluators

Eighteen (18) senior mechanical engineering students enrolled in a semester-long mechatronics course were selected for their participation in this research study. The selected students were randomly divided into two groups, each group consisting of 9 students. Furthermore, 3 senior engineering students and 3 graduate engineering students were selected to observe and evaluate the instruction. This team was called the 'evaluation' team of the research study. The evaluation team participated in the research study voluntarily.

4.2 The teaching topic and the classroom setting

The instructor selected a topic to be instructed in the mechatronics course based on the mechatronics curriculum of the university. The topic was the introduction to a robotic manipulation system. The instructor planned to instruct the selected topic in a 50-minute class period in mechatronics lab room with instructional facilities.

4.3 Pedagogies

It was planned that the instructor would follow two different pedagogical approaches to instruct the selected topic of the mechatronics course: (i) TPACK framework-based instructional approach, and (ii) ordinary (traditional) instructional approach. In the TPACK framework-based instructional approach, the instructor identified the necessary knowledge, skills, expertise and facilities of each knowledge domain and subdomain of the TPACK framework to instruct the specific mechatronics topic, took necessary preparations to meet all necessary knowledge, skills and facilities, and then instructed the topic to the students. However, in the ordinary instructional approach, the instructor did not align his preparation for the instruction of the topic with the requirements of the knowledge domains and subdomains of the TPACK framework. Instead, the instructor took overall preparation to instruct the topic. For the ordinary (traditional) instruction, the instructor followed the instruction design for the topic that the instructor received from another instructor of the topic who was not aware of the TPACK framework. The ordinary instructional approach might eventually include some of the activities that the instructor planned under the TPACK framework, but those were not intentionally decided and planned by the instructor to instruct the topic under the ordinary instructional approach.

4.4 Design of the research

The research methodology adopted for this research study was the observation of the instruction by the evaluation team and comparison of instructional outcomes between two different pedagogies (TPACK framework-based instructional approach, and ordinary instructional approach) by the evaluation team. In this research study, the pedagogical approaches were the independent variables, and the instructional outcomes were the dependent variables.

4.5 Development of resources

For the TPACK framework-based instruction, the instructor determined the knowledge, skills, expertise and facilities of each knowledge domain and subdomain of the TPACK framework necessary to instruct the selected mechatronics topic so that the instructor could make necessary preparations to meet all necessary knowledge, skills and facilities before instructing the topic to the students. Table 1 shows such preparation of the instructor aligning with the TPACK framework [2]-[4]. Meeting the requirements of each knowledge domain in Table 1, the instructor prepared necessary PowerPoint slides to instruct the topic. The instructor also developed necessary handouts on the topic to be distributed to the students. The instructor developed paper-based worksheets that the students needed to use during the instruction. In addition, the instructor developed a working prototype of a robotic manipulation system, as Fig.1 illustrates. The instructor also developed a set of test questions relevant to the content of the topic for testing the learning outcomes of the students, as Appendix A shows. The instructor also developed assessment questionnaires that the evaluation team could use to assess socioemotional attitudes (e.g., engagement, enthusiasm) of the students after their participation in the instructional session, which Appendix B shows.

Table 1. Requirements of knowledge, skills, and expertise for each knowledge domain and subdomain of the TPACK framework for instructing the selected topic in mechatronics.

TPACK domain/subdomain	Requirements of knowledge, skills, and expertise
CK	• Knowledge of the overall configuration of the robotic manipulation system, its components, main functions of each component, how the components are connected to each other, how the components are interfaced with the software, programming or coding, communication protocols, etc. • Knowledge of working principles of different types of sensors used in the system, data acquisition, data analysis, etc. • Working principles of the actuators used in the system. • Knowledge of safety protocols with the system.
TK	• Knowledge, skills and experiences of how the robotic manipulation system can be operated and demonstrated to students for a complete manipulation task. • Knowledge, familiarity, skills and abilities to use different facilities and resources of the classroom required to instruct the topic, e.g., computers, multi-media projector with the audiovisual system, white screen, lighting bulbs and switches, electrical power outlets, internet services, TV monitor with remote operator, whiteboard, marker pens, eraser, etc.
PK	• Knowledge of deciding the delivery method and activities during the instruction of the topic, e.g., determining portions, timing and sequence of verbal lecture, writing on board, showing in projector, demonstrating the robotic system, dialogue, reflection, etc. • Knowledge of questioning and answering techniques, ideal body language, eye contact, etc. of the instructor that matches different situations or events during the instruction.

	• Knowledge of evaluating students such as how to develop and administer tests, assignments, etc. to evaluate students.
TPK	• Knowledge of planning the pedagogy for instructing the topic and checking if the available and planned technologies are appropriate for the planned pedagogy, and vice versa. • Knowledge of impact and contribution of the planned technologies on pedagogical quality.
TCK	• Knowledge of how to analyze the functions of the available technological facilities and resources and check if these are sufficient and appropriate for explaining the specific content knowledge. • Knowledge of determining the suitability of the content knowledge and planned classroom technologies, and vice versa.
PCK	• Knowledge of analyzing if the planned pedagogy is appropriate to deliver the content knowledge properly.
TPACK	• Knowledge of analyzing the relative importance of and interconnection between each of the knowledge domains and subdomains. • Knowledge of analyzing how the instructor can compensate for lack of self-efficacy in one knowledge domain by another knowledge domain or subdomain. • Knowledge of analyzing how lack of self-efficacy in one domain can impact another domain or subdomain.

4.6 Research procedures

There were two phases in the research procedures. In the first phase, the instructor instructed the selected mechatronics topic to the first group of students (9 students) following the TPACK framework-based instructional approach in a 50-minute instructional period in the classroom plus lab setting. The evaluation team members were present during the instruction to observe the instruction and assess the instructional quality of the instructor individually following a 7-point Likert scale. Here, the instructional quality means how competently the instructor prepared him to align with the requirements of each knowledge domain and subdomain of the TPACK framework, and how effectively the instructor delivered the instruction meeting the requirements of the TPACK knowledge domains and subdomains. Then, the instructor administered a written test for evaluating the learning outcomes of the students based on questions developed by the instructor shown in Appendix A. However, the answers to the questions written by the students were evaluated by each member of the evaluation team. The identity of the students was not written on the answer sheets. By evaluating the answer sheets, the evaluation team determined the learning outcomes of the students for the topic they were instructed. Then, each evaluation team member individually assessed the socioemotional attitudes such as the level of engagement and enthusiasm of each student based on their observations on the students during the instruction period following the 7-point Likert scale shown in Appendix B.

In the second phase of the research study, the instructor instructed the same topic to the other group of students (9 students) following the same procedures as the above, but the instructor followed the traditional instructional approach. It means, the instructor followed the instruction design for the topic that the instructor received from another instructor of the topic who was not aware of the TPACK framework. The ordinary instructional approach might eventually include some of the activities that the instructor planned under the TPACK framework, but those were not intentionally decided and planned by the instructor to instruct the topic. The evaluation procedures for evaluating the instructional outcomes for the ordinary instructional approach were also the same as that applied to the instruction that followed the TPACK framework.

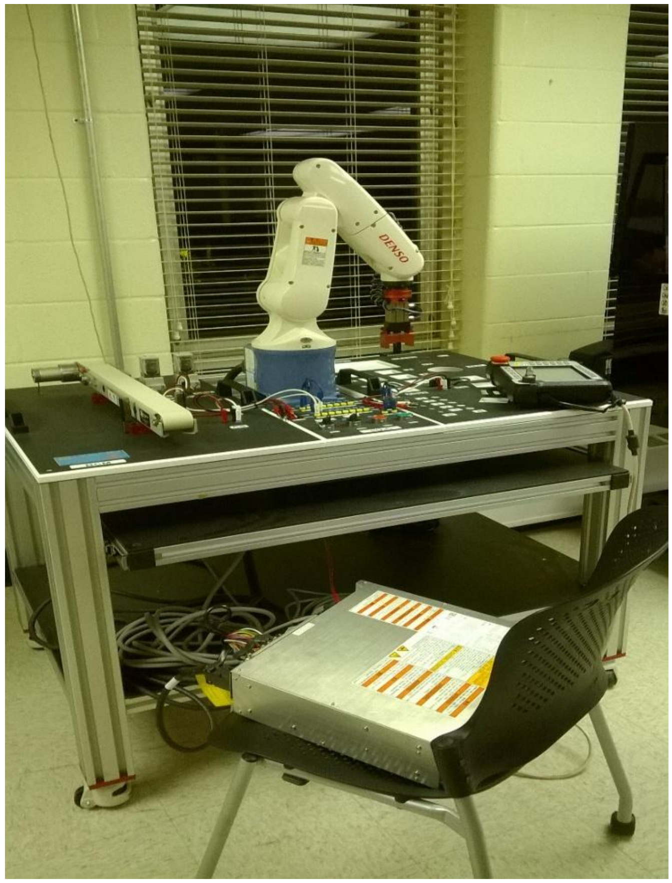

Figure 1. The robotic manipulation system developed (interfaced, programmed) by the instructor to use it as a working model in instructing the selected topic to the students.

In both phases of the instruction, the evaluators did not ask questions to the students verbally or directly to evaluate the instructional outcomes and assess their socioemotional attitudes for their participation in the study. Instead, the evaluation team members assessed and evaluated the students based on their answers to the questions written on answer sheets and on observations on the students during the instruction sessions. In both phases, the instructor instructed the mechatronics topic to the students in such a way that the correct answers to the questions set in Appendix A were embedded in the instructions and it might be possible for the students to know and understand the answers to the questions set in Appendix A.

4.7 Research results and analysis

Figure 2 shows the mean efficacy assessment scores of the instructor for different knowledge domains and subdomains assessed by the evaluation team between the traditional (ordinary) instructional approach and the TPACK-based instructional approach. The assessment scores reflect instructional qualities of the instructor for the topic. The results show that the instructor's knowledge in different knowledge domains and subdomains increased as the instructor followed the TPACK-based instructional approach [8]. This is because the instructor aligned the preparation for the instruction with the requirements of each knowledge domain and subdomain purposefully for the TPACK approach. The assessment results also show that the instructor was somewhat able to meet the knowledge requirements of different TPACK domains and subdomains even when the instructor followed the traditional instructional approach. This is because the instruction indirectly and eventually met some knowledge requirements of the TPACK domains. This is why the assessment scores for the traditional instructional approach were low, but not zero [2], [8]. The results in Fig.2 show that the efficacy of the instructor in CK was high for the traditional instructional approach. The efficacy in PK and TK was also high in the traditional instructional approach. This is because, under the traditional instructional approach, instructors usually focus on CK and PK, and they sometimes focus on TK. However, they are not aware of TPK, TCK, PCK and TPACK knowledge subdomains under the traditional instructional approach. The results in Fig.2 show that the efficacy in these knowledge subdomains significantly increased under the TPACK instructional framework as the instructor intentionally and purposefully prepared on those knowledge subdomains to meet the requirements of the TPACK framework. The results of paired *t*-test showed that the assessment scores between the two pedagogical approaches were statistically significant ($p<0.05$), which indicates the superiority of the TPACK-based instructional model over the traditional instructional model [5].

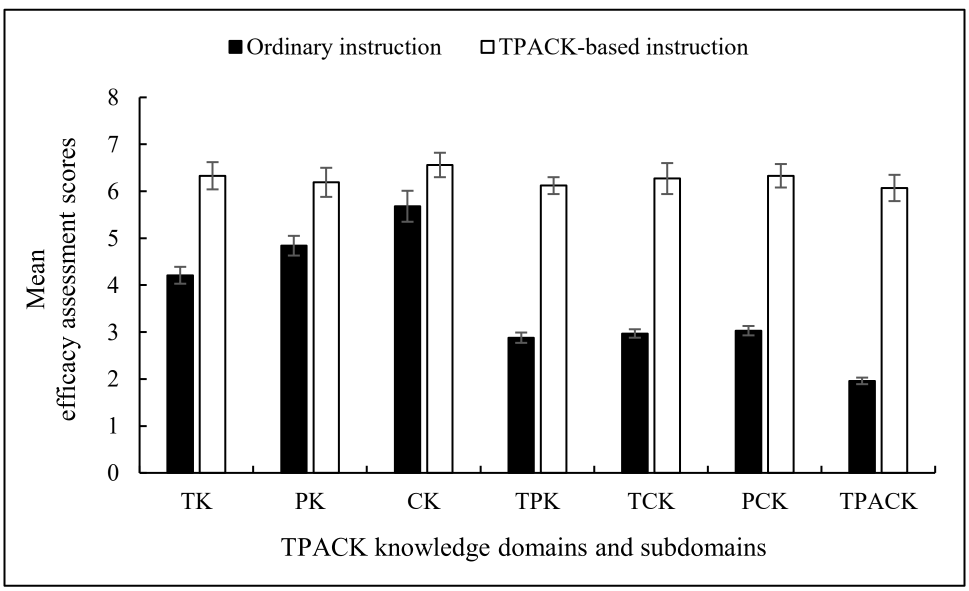

Figure 2. The mean efficacy assessment scores for different knowledge domains and subdomains reflecting instructional qualities of the instructor assessed by the evaluation team between the traditional (ordinary) instructional approach and the TPACK-based instructional approach.

Table 2 shows the mean test score for each question (standard deviation in parenthesis) between the two student groups. A paired *t*-test conducted on the test scores between the two student groups showed that the test scores between the two groups were statistically significant ($p<0.05$). The results clearly show that the instructional outcomes significantly improved for the TPACK-based instructional approach compared to the traditional instructional approach. It is observed that the instructional outcomes for traditional instruction were also satisfactory, but the TPACK-based instructional model produced better instructional outcomes in terms of knowledge of the students in the subject matter. It happened because the traditional instructional approach might also be a good instructional approach that might indirectly and eventually help the instructor meet the knowledge requirements for the instruction partly [5], [8].

Table 2. The mean test score percentage (%) for each question (standard deviation in parenthesis) between the two student groups.

Question number	Test scores % for traditional instruction	Test scores % for TPACK-based instruction	Difference between scores (%)
1	84.19 (2.32)	95.06 (3.39)	+10.87
2	81.45 (3.51)	96.28 (3.04)	+14.83
3	80.82 (2.64)	94.23 (3.12)	+13.41
4	83.94 (2.86)	93.47 (3.35)	+9.53
5	85.47 (2.98)	96.74 (3.22)	+11.27

Table 3 shows the mean assessment scores of socioemotional attitudes of the students (engagement and enthusiasm) rated by the evaluation team members for the two student groups. The results showed that engagement and enthusiasm significantly improved due to the TPACK-based instructional approach. The paired *t*-test results showed that the assessment scores between the two student groups were statistically significant ($p<0.05$). It is assumed that the systematic, well-planned and well-prepared instruction meeting necessary knowledge and skill requirements of the TPACK approach helped the instructor perform the instructional activities properly, which drew attention of the students and attuned them with the sequential propagation of the instruction, which might enhance engagement of the students in the topic they learned. Similarly, the TPACK approach presented the contents of the topic more rigorously and enhanced students' interest in the topic, which might enhance their enthusiasm in learning and mastering the topic [1], [5], [8].

Table 3. The mean engagement and enthusiasm assessment scores (standard deviations in the parentheses) between the two student groups.

Assessment Criteria	Mean scores for the traditional instruction	Mean scores for the TPACK-based instruction	Difference between the scores
Engagement	5.26 (0.20)	6.58 (0.24)	+1.32
Enthusiasm	5.09 (0.14)	6.53 (0.22)	+1.44

5. Discussion

It is assumed that there are challenges that instructors may experience while designing and instructing topics following the TPACK model. For example, it may be difficult for instructors to develop the framework of TPACK-based instruction illustrated in Table 1. It seems to be challenging for instructors to wholistically determine the knowledge requirements for each domain and subdomain of the TPACK framework [2]. It is assumed that determining the knowledge requirements for the TPACK subdomains may be more difficult as they need instructors to determine the knowledge of one domain that is related to another domain, and understanding such cross-connections is usually difficult [8]. Delivering the entire lesson addressing all the knowledge requirements may be difficult for some instructors. If the TPACK framework is not developed by instructors for the topics to be instructed properly, then they also cannot make good preparations for the instruction. As a result, the instructional outcomes of TPACK-based instructions may not be met. Selection of wrong or irrelevant activities due to failure in determining required knowledge domains or subdomains may jeopardize the mission of applying the TPACK model in instructions. Wrong or irrelevant activities may also create misconceptions in students about the topic to be instructed. Development of the TPACK model as Table 1 illustrates is also time consuming, which creates burdens on instructors [4]-[5].

Instruction designers (instructors) need to make all facilities and resources available to meet the knowledge requirements of each domain and subdomain during the instruction period, which may also be difficult for instructors, and they may need support from institutions to overcome such burdens. Instructors may identify limitations of the instruction of a topic following the TPACK model and develop an action plan containing corrective actions for continual improvement (CI) of the instructions. The design-based research method can be used as the CI tool to ensure continual improvement of the instructional quality [8].

6. Conclusions and Further Research Needs

In this paper, a topic in the mechatronics course (robotic manipulation system) was taught to two different groups of students by the same instructor in the same classroom setting following two different pedagogical approaches: TPACK model-based instruction and traditional instruction. An independent evaluation team observed both instructions in person, and then the team members independently and individually assessed the instructional quality and evaluated the instructional outcomes for both instructional (pedagogical) approaches. The results showed that the TPACK-based instructional approach significantly enhanced the instructional quality and instructional outcomes. Then, the challenges and burdens in designing and implementing the TPACK model were discussed. The results proved the prospects of the TPACK instructional approach in instructing mechatronics and similar topics, which can encourage and guide instructors, educational researchers and policymakers to apply TPACK method for instructing mechatronics and similar STEM courses.

In the future, further research will be conducted to determine the knowledge requirements for each knowledge domain and subdomain more rigorously. Resources and facilities needed to meet the knowledge requirements for each knowledge domain and subdomain to optimize the instructional outcomes will be determined more critically. The results obtained herein will be verified using larger number of students, instructors and evaluators for more STEM topics to ensure the generality of the results.

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Appendix A: Test questions set

1. What was the objective of using the robotic manipulation system?
2. What were the main components that were used to develop and operate the entire robotic manipulation system?
3. Write about the main function of each component of the robotic manipulation system.
4. What were the working principles of the sensors used in the robotic manipulation system?
5. How were the hardware components interfaced with the programming (coding) environment? Give an example.

Appendix B: Socioemotional attitudes assessment

1. The students were found engaged in lesson activities during the instruction. (circle one)

   1 (least) 2 3 4 5 6 7 (most)

2. The students demonstrated significant interest and enthusiasm in the topic and related areas. (circle one)

   1 (least) 2 3 4 5 6 7 (most)