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Cultivation of the Students' Critical Thinking Ability in Numerical Control Machining Course Based on the Virtual Simulation System Teaching Method

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ABSTRACT Critical thinking is an important part of the quality cultivation of engineering students. At present, many colleges and universities in China have gradually realized it, and mainly strengthen the training of students' critical thinking by offering relevant humanities courses, but there are few researches related to this topic through the penetration of engineering professional courses, and they are not deep enough. This study mainly discusses the efficacy of virtual simulation system teaching method in improving critical thinking of engineering students engaged in NC (Numerical Control) machining. It integrates the types of learning activities in the proposed teaching method with the development elements of critical thinking, and then constructs the context-based teaching design along with a self-developed virtual learning environment for the cultivation of students' critical thinking. We also evaluated students' response towards the research topics to investigate its teaching-learning effectiveness and acceptance by student community. Responses from questionnaires were collected from a convenience sample of 63 junior students majoring in NC machining from the author's university. The subsequent empirical study was conducted to exhibit superior results for mostly the cognitive skills of critical thinking. Students' feedback also revealed that students obtain more satisfaction and self-confidence, and demonstrated high positive attitude towards the proposed teaching method, and showed high perceived usefulness of the context-based teaching design to acquire complete, concrete and confident knowledge of NC machining. The findings of this study are valuable for academic institutions and educators to design the virtual visualized lectures and classrooms to enhance students' performance in critical thinking.

INDEX TERMS Critical thinking, empirical study, computer-supported collaborative learning, NC machining course, virtual simulation system teaching method.

I. INTRODUCTION

As we live in a world with an increased attention to the sciences, this explosive growth of scientific knowledge and its implications intrinsically affect everyone's lives. In truth, never before has there been a pressing need for students and the public to be prepared to take a stand in science issues, detect fallacies in arguments, and provide rational and logical decisions on societal issues, which can all be achieved by possessing critical thinking (CT) skills [1]. CT plays an important role in the contemporary information society, which is conducive to improving the learning ability of college students, so that they could better adapt to the future social development. Nowadays, CT has been recognized as

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one of the two basic skills of thinking as well as the problem-solving ability [2]. It can be said that CT requires thinking deeply, being active, having purpose, being conscious, questioning, judging, thinking what to believe or not, and thinking what to do, and regarding these while deciding [3]. As an indispensable part of knowledge learning, CT is a kind of thinking activity of understanding, processing and transmitting the information in the process of solving problems, understanding experiences and creating ideas. There needs to be feasible research programs that allow different methods to be developed and trialed in higher education over extended periods.

Nowadays, scientific and technological innovation ability is an important context to measure the quality of personnel training in engineering colleges. Developing optimum solutions to engineering problems typically relies on structured and complex thought processes that require evaluation, interpretation and opinion. Well-developed CT skills are essential for dealing with the multi-dimensional nature of these problems [4]. Over the last decade, there has been an increased focus on developing CT skills within the engineering education [5]. It can be said that the cultivation of CT ability has become an important link in improving the quality of personnel training in engineering colleges. At the same time, CT is the logical prerequisite and driving force for engineering students to improve their innovation ability. Although the development of CT skills has emerged as an important issue in engineering education, implementation of pedagogies targeting these skills across the engineering disciplines has proved challenging. Fostering CT of engineering students is a systematic project involving educational concept, teaching content, teaching methods, curriculum system, etc. From the perspective of teaching, it is quite meaningful to discuss how to facilitate the development of CT by adjusting the curriculum plan and content, and changing the teaching methods or modes in the teaching process. CT in an engineering context is well reported in teaching and learning academic literature, however, much of this is framed within theoretical and conceptual frameworks. Practical approaches of how CT skills are best promoted in engineering curricula are less common.

For this reason, this study hopes to investigate the performance of the context-based teaching designs along with a self-developed VR computer numerical control training environment for the cultivation of the students' CT. And a state-of-art review of practical intervention that targets the development of CT in engineering students is presented. That is, the proposed virtual simulation system teaching design were first developed for this study, by the aid of the latest development results of virtual reality technology in the field of NC machining simulation. It will exploit the entire design process of NC machining simulation system into an innovative practice training project of NC teaching, and regard the UG/ISV integrated simulation & verification module as the platform to explain NC processing-related knowledge from the perspective of the system, so that students will further into the attempt to establish NC machining simulation system from the previous simple application.

Furthermore, we take the typical parts as an example to verify the virtual simulation of the whole NC machining process. In this way, the teaching content which supposed to be finished only by several intermittent training programs can be organically combined into a comprehensive and innovative training project through NC machining simulation system, emphasizing the integrity, practicality and synthesis of the project. Secondly, this article concerns itself with the examination of NC learning performance issue of the students majoring in NC machining from the perspective of CT. We will implant CT into the learning activities in the proposed teaching method. Activities included the process-oriented guided-inquiry learning, model building, case studies and targeted CT exercises. Our goal was to assess the impact of targeted interventions in NC machining course and focuses on teaching activities where their effects in promoting CT skills in students are measured. Thirdly, to more robustly and holistically ensure that CT is clearly embedded in NC machining course, the empirical study on virtual simulation system teaching activities promoting the development of CT skills was experimented in NC machining classroom and 63 junior students were recruited from the department of mechanical engineering of the author's university. Then, the corresponding pretests, teaching activities and posttests were implemented based on the proposed teaching designs. Finally, the questionnaire-based performance evaluations were utilized to conduct the final comparison and conclusion. And the corresponding research findings are further explored to establish solid theoretical and practical basis for the application of CT in engineering education.

The remainder of this article is organized as follows. Section 2 provides a description of the related work and the uniqueness of this article. Section 3 presents a detailed description of the virtual simulation system teaching method for NC machining course based on virtual simulation technology, and discusses the implementation of the teaching method in cultivating the students' CT ability. Section 4 presents an experiment carried out by the junior students majoring in NC machining in the engineering college of the author's university. The design of the evaluation rubric and the correlation questionnaire for assessing the students are also presented. Section 5 provides the results in both quantitative and qualitative manners, the corresponding discussions and findings about the insights gained from this study. Finally, Section 6 and 7 presents the conclusions and future work of this study.

II. LITERATURE REVIEW

This section introduces the relevant research literature and the educational technology that enable to promote the cultivation of CT ability for college students. And some implications for curriculum design and implementation in relation to CT are presented. We also describe the advantages of virtual simulation technology applied in NC machining course, as well as the possible challenges faced in the teaching practice.

A. CRITICAL THINKING TEACHING METHODS

During the last two decades students at higher education are being more exposed to the concept of CT as a way to improve not only their professional skills, but their personal capabilities as members of a global community [6], [7]. CT is a purposeful, self-regulatory thinking in which individuals systematically and habitually impose criteria and intellectual standards upon their thought processes [8]. The development of CT has been one of the most essential objectives in many educational areas for many years, mainly involving economics [9], literacy [10], geography [11], mathematics [12], and higher education [13]. In fact, the teaching of CT is of vital importance to all students in all subjects, because all subjects require you to ask questions, relate theory to practice, find and use appropriate evidence, evaluate, find links, and categorize. For this reason, the university must do its best to integrate it into the syllabus, curriculum and classroom [14]. Any subject teaching should include imparting CT knowledge, developing CT skills, and aiming at cultivating critical thinkers with CT attitudes and habits, so that they are willing and good at CT when appropriate [15].

CT is an urgent research hotspot in the field of undergraduate education, because it is the essential foundation for students in economic, social, political and daily life of the 21st century and thereafter. No matter in life or in the professional field, everyone may fall into the dilemma of not knowing what to believe or what to do. However, people who are proficient in CT are more likely to find satisfactory solutions than those who do not reflect or respond by instinct. Those who tend to handle the difficulties with the skillful CT can better control their lives. Generally, most people will develop some CT habits or skills more or less in the process of growing up, especially in school education. In fact, those education models with special emphasis on the knowledge, skills and attitudes of the critical thinkers will greatly improve their quality in this respect.

CT training is an important goal of university education, and also the key to cultivate high-quality innovative talents. In general, CT is composed of attitude dispositions (critical spirit) and skills (intellectual skills) [16]. One of its core contents is to improve the people's practical demonstration ability by cultivating logical thinking ability, and to train the ability of information analysis, reasoning and evaluation through detailed argumentation skill training. Another core content is to cultivate the thinking habit guided by behaviors with the help of the skills mentioned above, and to cultivate the spiritual temperament of being bold in questioning, rational thinking and introspection.

Although the definition of CT is not unique to a single discipline, there are still some debates about whether CT could be taught in general courses or be independent of other disciplines [17]. At present, there are two main opinions on the teaching method of CT: the first is to advocate a special course of CT, and the second emphasis on the combination of CT training and specific disciplines. It can be said that there are many new courses about CT in undergraduate education every year, but a preponderance of scholars argue against such stand-alone courses, mainly because they discover CT is more successfully taught within the context of specific subject knowledge [18]. After years of practice, many research results show that it is more effective to integrate CT into specific disciplines. Hence, how to carry out classroom teaching of CT to improve students' thinking ability is still an important field worthy of further study.

CT ability of college students can be improved only through systematic training program. The crux of the matter lies in how to effectively deal with the relationship between CT training and specific subject education [19]. Thinking training is not just the responsibility of specific courses, such as logistics, psychology or pedagogy. Thinking can not be separated from the process and content of education, and each course should guide the students how to engage in the interpretation, analysis, evaluation, reasoning and explanation for the research content in the context [20]. The teaching method of CT requires the professional teachers to impart professional knowledge and develop CT spirit throughout the teaching activities, while imperceptibly guiding students to master CT skills. In order to strengthen the training of CT ability and innovation ability of students, it is necessary for specialized courses teaching to consciously cultivate the students' multiple thinking ability, involving analysis and synthesis, abstraction and generalization, multi angle observation and innovation consciousness, so as to point out the problems and solve them [21].

David pointed out that the best way to teach CT is to use CT to inspire students to think actively, and encourage them to engage in exploration and creation activities from a personal sense [22]. Therefore, the primary purpose of teaching is not simple to impart knowledge to the students, but to find a variety of teaching methods to mobilize the enthusiasm of students to actively participate in the teaching activities. At the same time, the learning process should be combined with the practice, and encourage students to conduct multi-angle exploration and debate for specific issues. The fundamental goal of teaching is to make students willing and able to devote oneself to evidence analysis, reason inquiry, open-mindedness and being good at practice, and constantly urge students to explore different facts, opinions, explanations and arguments. Therefore, to cultivate the students' ability of CT and problem-solving, classroom teaching needs to be designed consciously to enable students to focus on the state of self thinking, so as to carry out behavioral reflection and rational criticism. In this way, the students could carry out specific practical reasoning and detailed demonstration, and open their minds to use imagination to analyze various possibilities, procedures and consequences, so as to explore new knowledge and then take effective actions.

B. REVIEW OF VIRTUAL SIMULATION SYSTEM TEACHING METHOD

Virtual simulation technology combines image processing, pattern recognition, computer graphics, sensing technology, intelligent technology, network technology, voice processing, audio technology and other science, transforming the digital information of computer processing into multi-dimensional information people can perceive [23]. Users may make a dynamic interaction towards the control behavior through the visual, listening, touch and other perceptions.

With the diversified development of contemporary education, a single teaching mode alone will not be sufficient to solve the limitations of the students' innovative thinking and creativity [24]. System teaching method usually emphasizes that teachers need to arrange teaching contents systematically, so that students could strengthen their understanding of the interrelated knowledge learned from the perspective of the integrity, sort out the main line of the course, pay attention to the mutual connection and penetration of different knowledge points, and eventually grasp the integrity and systematic nature of the whole course [25]. Students can not only learn and master the basic knowledge of all chapters and sections, but also make each component of the given system organically combined, integrated and comprehensively used.

From the perspective of systematic thinking, the cultivation of the students' CT consciousness and skills is a systematic project [26]. The core task of CT training lies in the unity of cultivating critical spirit, mastering critical skills and enhancing practical ability [27]. In constructivist view, the learning is a constructive process where the learners construct their own understandings, and knowledge cannot simply transfer from one person to another because it is not a pure copy of the external world [28], [29]. Constructivism is a student-centered instructional design approach in which the learning is treated as the development of a personally meaningful understanding of content, developed through interactive experiences with stimulus materials and problems in a realistic context [30]. Wilson (1996) defines constructivist learning environment as a place where learners may work together and support each other as they use variety of tools and information resources in their guided pursuit of learning goals and problem-solving activities [31]. The virtual simulation system teaching method proposed in this article was based on the constructivist learning theory. It uses the distinctive virtual simulation technology to transform the actual application scene into virtual simulation system through the equivalent description of the actual production process. Next, after introducing it into the classroom through reasonable and effective teaching design, we can carry out the systematic teaching method in the virtual environment. This would provide students with a good multi-channel learning opportunity to engage in exploratory research and creative thinking in innovative teaching situations. Moreover, the interaction of multi-dimensional information between human and the virtual environment makes the students have a sense of being in the real world, so that students could have an immersive experience for the criticality of problem evolution and solution in the real process. In addition, through virtual operation, parameter adjustment and process analysis, the students' thirst for knowledge is aroused to take a critical attitude towards their existing knowledge and conclusions and constantly improve them, experience the variability and complexity of the actual production process, so as to form a deep perceptual impression and finally realize the enhancement of CT skills.

C. REVIEW OF NC TEACHING

As Numerical Control (NC) technology is getting more and more progress, NC machine tools have been widely used in the field of the mechanical processing industries, and many companies are in great need of NC technical personnel, in which case some NC technology courses have been set up in the mechanical engineering specialty of most colleges and universities [32]. NC machining course is an undergraduate course in the authors' university. It is because NC teaching needs great theoretical depth and practicality that students find it difficult to learn it well. Moreover, it is hard to attract the students' attention by simple monolithic explanation in classroom. NC professional knowledge was traditionally taught as an isolated body, but the fact is that it also has to be learned for understanding, application, analysis, evaluation and creation. Therefore, it is of great value for us to find the suitable teaching method. With this in mind, several attempts have been made to find new educational approaches to enhance the students' learning motivation.

NC machining courses usually involve interpreting, describing, predicting and identifying the causal relationships within a machining framework. In particular, the virtual simulation system teaching design for NC machining course seems prone to developing such skills. Integrating CT with other capabilities, like guided inquiry, experimenting, seeking evidence with support, teamwork and communication, to form a few of NC machining-related skills, which can easily be enhanced through the development of CT skills. Consequently, NC teaching can be improved if it is taken to higher levels by aiming at CT through scientific experimentation, variable manipulation, data collection, deeper analysis, and integration of knowledge and processes. Moreover, the students will learn the most when they experience learning activities themselves, and where they apply CT skills with some assistance. In short, CT can contribute toward a better understanding of NC professional knowledge, to prepare students to act in the context of problem-solving and decision-making with regard to NC machining.

D. OVERVIEW OF TEACHING METHODOLOGY IN THIS STUDY

In the era of artificial intelligence, personal capabilities and qualities are being more demanded, such as emotional intelligence, teamwork and intrapersonal capabilities. Over the past decade, the development of CT has also emerged as a fundamental goal for engineering education [33]. At present, engineering education research has widely studied CT and reasoning [34]–[36]. CT and its related education model have become the research focuses of the engineering education [37], [38]. the engineering courses plays a major role in providing opportunities for students to use and acquire higher-order thinking skills. Yet, some researchers have voiced concerns about students' inability to think critically, mainly because there are many arguments that teachers do not know how to teach CT skills or the way to integrate CT skills in their teaching strategies [39], [40]. Therefore, there is still much work to be done since there is not a clear definition of this capability, and also new active methodologies need to be enhanced for its development.

Dresseletal pointed out that if the teacher used the appropriate teaching methods and chose the appropriate teaching content, CT ability of students would be improved [41]. Duron, Limbach, and Waugh add that CT is facilitated through practical activities which is expected for the student to promote this capability should be included in the teaching planning and methodological elements [42]. Veronika, Roman, and Stanislav also insist on the need and importance of focusing CT in the curriculum design of subjects [43]. Considering that different disciplines are characterized by particular approaches to CT, it is very important for the teacher to plan their courses well, so as to integrate theoretical aspects with professional practice, and offer students these type of experiences to address complex questions. To do so, teachers should consider the purpose, level and type of experiences that best helps to achieve the objective set.

As far as NC machining course studied in this article is concerned, the integration of CT skills into the daily content and lessons of NC teaching is essential for achieving the important learning objective. Considering the limited teaching resources of the physical classroom and the impact of virtual simulation technology on traditional teaching ideas, based on the literature review of NC machining course, the virtual simulation system teaching method is considered to be more effective for the development of CT. More specifically, In the process of NC teaching, the virtual simulation system teaching method is based on the teaching design of NC machining simulation system [44]. It regards the students as the main body of the study, and encourages students to take the initiative to think, actively participate in the discussion and build their own NC machining simulation system. NC machining simulation system is the mapping of NC machining system composed of machine tools, cutting tools, fixtures and workpieces in the actual production process, and its entity model is the subject of systematic visualization. And it is composed of the standard parts library, virtual machine tool library, processing system environment, tool path generator, simulation checking module, post-processing and other parts. It is necessary to integrate the above-mentioned components in order to form effective and unique teaching method. It encourages students to observe things and ponder questions with scientific attitude based on facts. In this way, students might create new ideas and find new solutions to solve the problems, and play a positive and effective role in their studies. Figure 1 provides the frame design diagram of NC machining simulation system and respective strategies adopted in NC machining course.

CT process often requires knowledge and skills in a variety of disciplines, belonging to complex holistic thinking. It can be considered as an interdisciplinary thinking when individuals complete the complex tasks of the real world. Therefore, it is helpful for the development of CT of students when emphasize on integrating disciplines in interdisciplinary courses. NC machining simulation system is the comprehensive application of the knowledge involved in NC machining, covering most of the professional knowledge of that major. This article turns to the Integrated Simulation & Verification (ISV) module latest developed by UG software to complete the establishment of NC machining simulation system. First of all, in the process of establishing NC machining simulation system, we need to clarify the relationship among machine tool geometric assembly model, machine virtual controller, NC system post-processing, control system settings, motion model, workpiece, machine tool and fixture assembly model and other components. Besides, we need to explore the function and the interrelationship between the various aspects of the simulation system in improving NC teaching effect through the step-by-step system analysis, based on the situation judgment and thinking. CT is the process of actively and skillfully analyzing, applying, synthesizing, evaluating the information that governs beliefs and behaviors. This information is generated by observation, experimentation, reflection, reasoning, or communication. Secondly, in the process of dynamic machining simulation, the simulation of the actual processing of the equipment and the real processing environment will involve the definition and selection of blank, workpiece clamping, fixture, machine manual operation, machine tool installation and tool setting, NC program input, measurement, collision detection, processing functions, and also have the function of debugging, editing, altering and tracking. Students can support their views through the discussion and observation of rational concept and then effectively improve the rational thinking ability, and therefore make them derive from the precondition to the final conclusion to quickly improve the understanding and mastery degree of NC technology under safe and reliable circumstances.

At the same time, the simulation system has the characteristics of multi-system, multi-tool and multi-part, which can make the students use the acquired knowledge to develop NC machine tools in reality by custom and then further expand the scope of NC machining simulation, so as to provide ideal space for the cultivation of students' open and adventurous thinking, making the whole process of virtual stimulation teaching design better illustrate the process of seeking knowledge for college students has obvious stages,

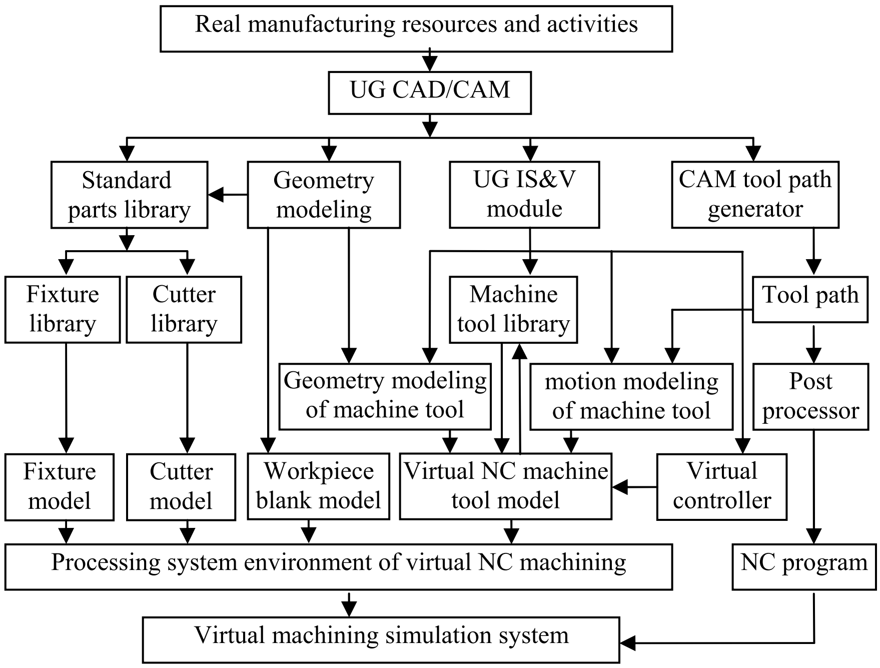


FIGURE 1. The frame design diagram of NC machining simulation system.

which is a process of evolution from simple to complex. Therefore, the students trained by comprehensive training program have made greater progress in their CT skills.

As far as the teaching is concerned, the simulation system has strong adaptability and generality. The students can accomplish the learning task of simulating complex thinking during the process of CT, and it is the process to complete the entire NC machining simulation system by using tools and resources, and as well as the process to enlighten and guide students to learn and explore themselves in the virtual reality environment. Besides, it focuses on creating a cooperative learning atmosphere. In the process of sharing knowledge and experience between each other, it can strengthen the students' ideological openness, self-confidence and systematization to encourage students to solve the problem in their own way through assessment and self-regulation process. Therefore, the construction process of NC machining simulation system is helpful to the formation of students' CT ability.

III. DESIGN AND IMPLEMENTATION OF THE VIRTUAL SIMULATION SYSTEM TEACHING METHOD

This section introduces the design and implementation of the virtual simulation system teaching method of teaching and learning in a course on NC machining. It will bring students another dimension to experience the felling of design and provides an efficient way of engaging students in active learning processes. Due to the fact that the integration of virtual simulation technology into the classroom provides innovative learning environments that allow for more interactive, relevant, and effective applications to give students valuable experiences, the course is well settled to introduce NC machining simulation system, as well as the use of such system tool for promoting collaborative learning and enhancing CT skills. This course is mainly for the junior students majoring in NC machining in the engineering college of the author's university, and provides them with the opportunity to experiment with ideas and see the results of their efforts on the computer screen. The basic idea of nurturing the learners through the teaching and instructional methodology is discussed in detail. The use of virtual simulation technology provides the means to shift the course toward a highly visual orientation and use computational techniques to solve real-world engineering problems. Furthermore, a well elaborative method of combining and implementing the proposed teaching method and CT is presented to promote the development of the students' CT.

A. INSTRUCTIONAL DESIGN

The curriculum content for this course is designed specially according to the construction process of NC machining simulation system, focusing on cultivating the students' CT. The first round goes by introducing the learners with the basic knowledge of NC machining simulation system. NC machining simulation system mainly simulates the cutting process of the whole machine tool, which will provide the learners with a dynamic, three-dimensional visual effect. The virtual simulation system teaching method takes the whole design process of NC machining simulation system as an innovative training project for students in NC teaching. The learners are then oriented and guided to build their own NC machining simulation system in groups by using the controlling gadgets and applications from the integrated simulation module of

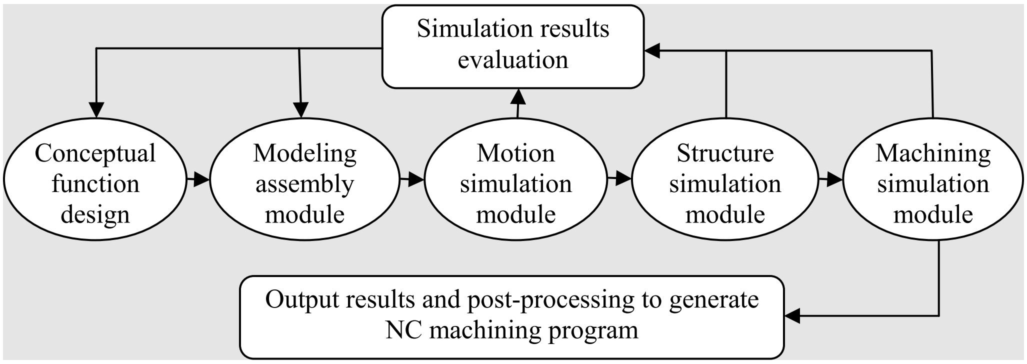


FIGURE 2. The logic diagram of implementation process of NC teaching activities.

UG software. The learners are also familiarized with the use of the machine control panel for guiding their engineering training project and keeping the track of different parameters as assigned through NC machining simulation system.

In the process of establishing NC machining simulation system, only by establishing an accurate motion model of NC machine tool, can the simulation results of the whole machining process fully conform to the actual situation, so that students can complete the comprehensive innovative engineering training project. It can be said that the students are also engaged in the learning task of simulating complex thinking in the process of establishing the whole NC machining simulation system. It tends to inspire and guide students to further explore knowledge in the virtual reality environment, enhance students' self-knowledge, self-esteem and learning motivation, and encourage students to solve problems in their own way. In a word, the construction process of NC machining simulation system is devoted to probing the principals and means of training students' CT in NC teaching activities. Figure 2 shows the logic diagram of implementation process of NC teaching activities under UG integrated simulation & verification environment.

1) UNDERSTANDING OF NC MACHINE TOOL STRUCTURE

Before constructing NC machining simulation system, we should first let students have a preliminary understanding of the research objectives from the working principle and overall structure of NC machine tool. Integrated simulation & verification of UG software is a fully customizable application module for simulating the cutting process of the whole machine tool. The machining process simulation in this environment can simultaneously display the solid models such as tools, workpieces, fixtures and machine tools, so that the whole machining system can carry out dynamic simulation in accordance with the kinematic chain of NC machine tool.

In general, the machine tool library of UG software itself comes with a lot of NC machine models (machining centers, milling machines, lathes, etc.) that have been assembled and debugged. However, in order to strengthen practical teaching links and train the students' practical ability, and focus on helping students acquire CT skills in facts, concepts, principles and theories of relevant disciplines through individual observation and experience, this study is not simple to allow the students to call the machine model from the machine tool library, but rather establish their own simulation model of NC machine tool specified in reality. As a kind of new attempt and challenge for students, it will enhance their learning enthusiasm and innovative ability, and effectively provide opportunities for students to show their expected disposition.

2) VIRTUAL ASSEMBLY MODEL OF NC MACHINE TOOL

In engineering education, mathematics and modeling are critical to developing and solving a physical problem [45]. The prerequisite for realizing virtual simulation of machine tool is the geometric assembly model of machine tool. This section focuses on training the students' practical hands-on mapping capabilities, 3D solid modeling and assembly skills. And it emphasizes CT skills of observation, comparison, classification and arrangement.

First of all, before the establishment of geometric assembly model, students need to understand the structural and movement characteristics of NC machine tools, and then effectively divide the bed part, machine tool holder component, X feed module, Z feed module and the spindle link of NC machine tool. Secondly, students need to grasp the movement path between the movement modules of the machine tool. According to the principle of "the former stage of the motor chain is assembled as the latter one" [46], the level and position of the motion modules in the whole assembly tree structure are gradually established. And until the students finally complete the tree structure of the whole machine tool assembly model, based on the bottom-up layer by layer assembly principle [47]. Finally, students need to go to NC machining site to collect the key dimensions of the moving parts of NC machine tools, and complete the parametric entity modeling of all components of NC machine tools in the three-dimensional modeling module of UG software, and then directly import them into the assembly module of UG software until the entire geometric assembly model of NC machine tool is completed. The geometric assembly model

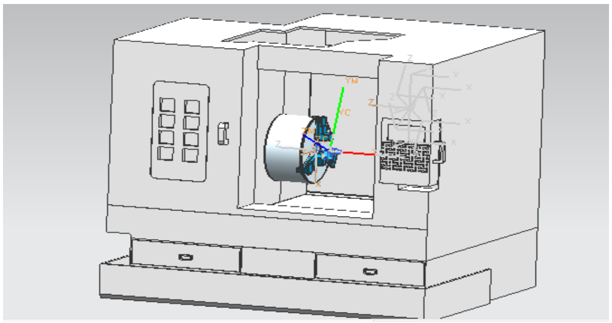


FIGURE 3. **The geometric assembly model of NC turning center.**

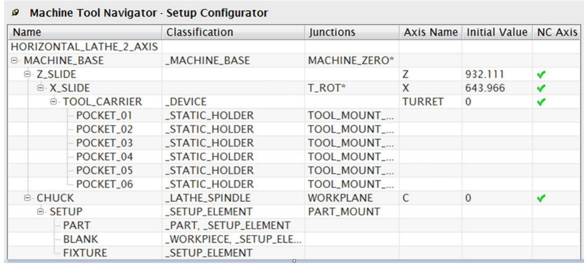
of NC turning center used for students' practical mapping is shown in Figure 3.

3) VIRTUAL MOTION MODEL OF NC MACHINE TOOL

The motion model of NC machine tool is based on the geometric assembly model of machine tool, which is used to describe the movement of machine tool. This research will guide the students to import the assembly model of NC turning center into the processing module of UG software. This part of work mainly involves specifying the moving parts of NC machine tool in the machine tool builder, determining the relationship between mutual movement position, and setting the travel range and moving direction of each moving axis, as well as the connection point of the machine tool. In this part, only when students fully grasp the motion mechanism and specific operating parameters of the actual NC machine tools, can they accurately set and define the simulation motion model of NC machine tool, which will help students have a certain degree of information literacy, with basic information searching, processing and communicating skills.

Taking NC turning center in the engineering training lab as an example, the primary task of students is to consult the relevant information and operation manual of NC machine tool. Through in-depth understanding of the general situation, performance parameters and operation process of the whole machine tool, the students could find out two main kinematic chains of NC turning center, and then define all levels of sub components of the motion model of NC machine tool, and further, through interdependent motion relationship of NC machine tool, carry out continuous discovery and meaning construction, strive to explore the deep-seated connotation, and finally complete motion model of machine tool, as shown in Figure 4. In this way, we focus on cultivating students' deep understanding of key concepts and strengthening their thinking skills in dealing with complex tasks.

The obvious effect of this part of teaching activities is that in order to be able to complete the entire NC machining simulation system, students will pursue a sense of achievement, and then generate a positive CT tendency, so as to take the initiative to understand the actual situation of NC machine tools studied and carry out large-scale reference and mining of the relevant data of NC machine tools. At the same



Machine Tool Navigator - Setup Configurator

Name	Classification	Junctions	Axis Name	Initial Value	NC Axis
HORIZONTAL_LATHE_2_AXIS					
MACHINE_BASE	_MACHINE_BASE	MACHINE_ZERO*			
Z_SLIDE			Z	932.111	✓
X_SLIDE		T_ROT*	X	643.966	✓
TOOL_CARRIER	_DEVICE		TURRET	0	✓
POCKET_01	_STATIC_HOLDER	TOOL_MOUNT_...			
POCKET_02	_STATIC_HOLDER	TOOL_MOUNT_...			
POCKET_03	_STATIC_HOLDER	TOOL_MOUNT_...			
POCKET_04	_STATIC_HOLDER	TOOL_MOUNT_...			
POCKET_05	_STATIC_HOLDER	TOOL_MOUNT_...			
POCKET_06	_STATIC_HOLDER	TOOL_MOUNT_...			
CHUCK	_LATHE_SPINDLE	WORKPLANE	C	0	✓
SETUP	_SETUP_ELEMENT	PART_MOUNT			
PART	_PART, _SETUP_ELEMENT				
BLANK	_WORKPIECE, _SETUP_ELE...				
FIXTURE	_SETUP_ELEMENT				

FIGURE 4. **A schematic diagram of the motion model of NC turning center.**

time, before using CT skills, they will maintain a kind of unremitting power in the process of interpretation, analysis and reasoning, and then achieve the synchronous learning of the combination of theory and practice, so that individual emotional tendency and subjective initiative can be integrated into the cultivation of CT. After completing the establishment of the whole motion model of NC machine tool, the students will have a deeper understanding of NC machine tool, which will be ready for the follow-up practical learning activities.

4) VIRTUAL DATABASE OF NC MACHINE TOOL

The successful completion of the motion model of NC machine tool led to the next phase of setting up the model database of NC machine tools. In this section, all the models of NC machine tools should be stored in the external database of the system. In order to ensure that the follow-up operation could successfully call NC machining simulation system, students should first grasp the file structure of model database, and be familiar with the setting mode of machine tool's name, type, structure form, NC system, control mode and other information in the database with the help of file code, as well as the storage location of related post-processing files. Then, students need to put the machine part files, motion model files, geometric assembly model files and virtual controller files created by themselves into the machine model directory in the database in the right way and path. The course design of this part takes full account of the way of processing knowledge to stimulate students' learning motivation and enable them to acquire meaningful specialized knowledge.

5) VIRTUAL CONTROLLER OF NC MACHINE TOOL

Generally, NC machine tool adopts digital control system to realize the movement and positioning control of the motion axis of NC machine tool and automatic tool changer. In the virtual environment, in order to simulate the real digital controller of NC machine tool, it is necessary to control the virtual motion axis of NC machine tool through the virtual controller of NC machine tool, and finally to realize the machining simulation. In this section, the students first use the virtual controller of NC machine tool to generate the motion control program and the simulation controller, and process all the behaviors and characteristics of NC machine tool, and then automatically generate the driving files, and further convert the preprocessed tool path into the corresponding control command. Next, the students call the corresponding S&V command to control the Boolean operation of each assembly part of the virtual machine tool, and simulate various motion tracks of the virtual machine tool, so as to realize the simulation of the actual processing status on the computer screen.

Virtual controller of NC machine tool is a key part of NC machining simulation system, and it is also a difficult point in the teaching process of the course. If this part of the teaching content is separated and explained to the students in the traditional teaching mode, students may have difficulty in mastering them due to the wide range, strong logicality and complex relevance of the teaching content. However, when NC machining simulation system is regarded as innovative engineering training program, students will consider and use the existing experience and knowledge in combination with CT, and further expand and modify these existing experience and knowledge according to the exploration, analysis and reasoning of new tasks, so that they will feel that the previously learned knowledge is no longer isolated and boring, so as to achieve mastery through a comprehensive study of the subject.

In addition, after completing most of the work in NC machining simulation system, for the sake of integrity, sense of mission and sense of achievement, student will spontaneously choose to face the difficulties, and stimulate strong learning interest and initiative for the rest of the last part of the learning content, until they finally build their own NC machining simulation system. What's more, if the students could successfully complete the assigned NC programming and processing tasks by themselves, it will further stimulate their self-confidence and enthusiasm for learning NC courses, and give full play to their inherent potential, so as to achieve the purpose of cultivating students' hard study and innovation spirit.

B. STRATEGY FOR THE INTEGRATION OF THE PROPOSED TEACHING METHOD WITH CT

Here, the strategy to cope up with the integrated learning technique to promote the development of CT is discussed. While designing and outlining the strategies for the new learning experience of the learners' CT, the influence of the virtual simulation system teaching method is highly kept in mind. This is because with the help of the virtual simulation system teaching method, we can better integrate CT into the teaching process of specific subjects, and the learners get more opportunities involved in the teaching process and pay more attention to the technical details of the subject matter.

To achieve the intentions, the teaching strategies based on the virtual simulation technology are designed in a way that focuses on the student-centered learning methodologies instead of the teacher-centered methods. This is because the traditional teacher-centered teaching techniques are considered obsolete in today's world for the sophisticated learning, especially for engineering students with strong logical thinking requirements, which suppresses the students' creative thoughts [48]. Moreover, it has been observed over the past few years that the student-centered virtual simulation learning environment allows the students for more active interpretation, analysis, evaluation, inference, explanation and self-regulation, and helps us to keep all the learners involved in the content. The resulting interactive learning module will also impose more responsibility on students for their own learning than the traditional lecture-based passive learning methodology [49], [50]. This tends to create a cooperative learning atmosphere for students, so that in the process of sharing knowledge and experience, the students can enhance their thinking openness, self-confidence and systematic ability through assessment and self-regulation. All in all, it will reflect a certain stimulative effect on the subtle cultivation of the learners' CT ability.

C. IMPLEMENTATION OF THE DESIGNED STRATEGY

This article will combine case-based instruction to carry out the execution of the designed strategy. The students are usually required to select the representative parts in the turning process as the machining objects, and then carry on the simulation case analysis of the turning process. In this way, students can participate in the design and implementation of the experiment process, and further practice CT skills in actual cases, so as to better grasp the teaching content, comprehend the key points of knowledge, effectively achieve the teaching target, and obtain better teaching results.

NC machining course is designed to ensure cognitive development in the learners. It focuses on encouraging them to work in groups and work out their embryonic teamwork. The course was divided into three phases, namely (a) the simulation preparation phase, (b) tool path simulation phase and (c) integrated simulation phase, as shown in Table 1. The students are given the opportunity to participate in the practical experience in the field of NC machining. At each phase, the complete descriptive teaching activity for the students was accomplished and the student-centered lecture planning is majorly focused.

As is mainly used in the previous NC teaching, the tool path simulation is only limited to the relative motion simulation between the cutting tool and the workpiece, as shown in Figure 5. In order to get a better simulation effect in accordance with the actual machining situation, it is necessary to extend the simulation of the whole NC machining process system, as shown in Figure 6.

The advantages of the integrated simulation is to observe the cutting process dynamically and intuitively, and simulate the actual machining situation of NC machine tool. Students can get feedback from the simulation environment, and then acquire the procedural knowledge, make learning plans and test learning overcomes within the framework of the above operating experience. If students encounter new problems, they will carry out orderly thinking analysis and process evaluation, and further clarify the research ideas and elaborate the technical routes, and finally complete the whole NC machining simulation process.

TABLE 1. Implementation methodology of the virtual simulation system teaching method.

Key phases of NC machining course	Strategies	Contents	Objects	Notes
(a) Simulation preparation phase	Cultivating the learners' interest with virtual simulation environment by showing the interesting videos of modern NC machine tool and their applications	introduction of the key components in the machining module of UG software, as well as their positioning relationship and orientation method	Establish the learners' cognition of NC machine tools and the processing module of UG software	Only the virtual machining system accurately simulate the whole operation environment of NC machining, the simulation results can fully meet the actual machining situation
(b) Tool path simulation phase	The learners must first master the primary tool path simulation, and then extend to the senior integrated simulation	Analyze the geometric characteristics of the typical workpiece, establish 3D solid models, complete the setting of blanks, workpieces, tools, machining procedures and methods, and specify the cutting parameters to realize the creation of all operation processes	Generate tool path simulation, and complete the visual verification as shown in Figure 5.	limited to the relative motion simulation between the cutting tool and the workpiece, focusing on simulation and demonstration of material removal
(c) Integrated simulation phase	Discusses the implementation of the teaching method in cultivating the students' CT ability based on the integrated simulation of NC machine tool	Through the operation navigator, the students transfer the ready-built model from the general machine library and realize the automatic assembly of NC machine tool, and then set the cutting parameters, and finally enter the simulation control panel of NC machine tool	Realize the whole machining process simulation of NC machine tool in Figure 6	All-round observation of the whole simulation process of NC machine tool, timely find out various possible interference and collision

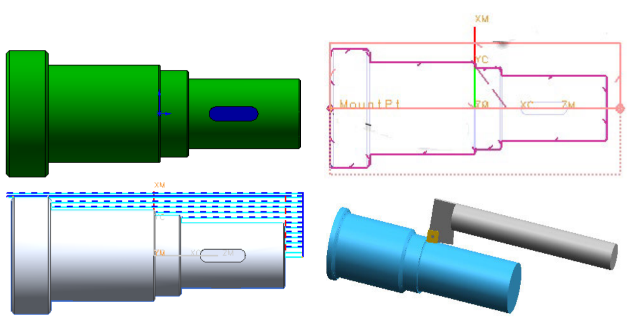


FIGURE 5. Tool path simulation of the typical part in NC turning centre.

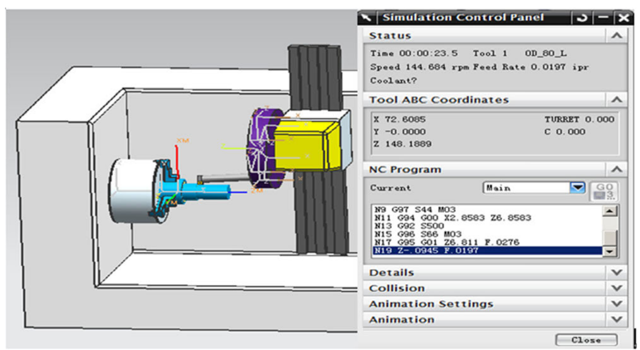


FIGURE 6. Comprehensive simulation of the whole NC machining process system.

CT is a purposeful and rational process of intellectual planning, including problem-solving, logical deduction, possibility calculation and decision-making [51], [52]. Coincidentally, the case analysis of the integrated simulation processing of NC machine tool and the subsequent thinking evaluation process just meet the above characteristics. It not only helps to train the students' cognitive ability, thinking strategy and thinking skills, enable students to grasp NC machining technology intuitively, but also facilitates to cultivate their CT tendencies such as inquiry, questioning and clarification, so as to effectively judge the continuity and rationality of the tool path movement. In this way, students can further deepen their understanding of NC machining technology in the virtual simulation learning environment. What is more, it also has contributed to the improvement and cultivation of students' comprehensive ability.

IV. MATERIALS AND METHODS

A. CCTDI (CALIFORNIA CRITICAL THINKING DISPOSITION INVENTORY)

This study adopts the CCTDI to conduct pre-test and post-test on the subjects. CCTDI is a set of tests designed for CT

TABLE 2. Total score statistics of students' CT dispositions based on the pretest and posttest.

	N	Minimum value	Maximum value	Mean value	Standard deviation	Variance	Skewness
Pretest statistics	60	237	319	279.63	18.16	329.66	0.153
Posttest statistics	60	315	371	341.5	11.49	131.98	-0.207

dispositions, published by the American Philosophical Society in 1990 [53]. It is a comparatively mature and widely used tool for testing CT emotion and attitude, which is suitable for college students, graduate students and adult professionals. Nearly ten years of research have shown that CCTDI has good reliability and validity. CCTDI totally has 75 items, being divided into 7 subscales to test the seven characteristics of CT respectively, which are truth seeking (T subscale), open-mindedness (O subscale), analytical ability (A subscale), systematic ability (S subscale), intellectual curiosity (I subscale), self-confidence (C subscale), cognitive maturity (M subscale). CCTDI adopts the Likert scale which ranges from "totally agree" to "totally disagree", and the negative items are assigned as "1, 2, 3, 4, 5, 6" while the positive items are in opposite direction. Each characteristic has 10 items, scoring at 10 to 60. The minimum recognition score of each characteristic who has the corresponding CT ability is 40. A score greater than 50 points indicates a strong corresponding CT ability. A total score lower than 280 indicates a weaker CT dispositions; between 280 and 350 indicates a neutral CT dispositions; no less than 350 a strong CT dispositions.

In this study, 63 copies of CCTDI measuring scale were issued, of which 63 copies were recovered and 3 invalid copies were excluded. That is to say, there are 60 copies valid, and the effective percentage is 95.23%. In addition, the Cronbach's reliability coefficient of the scale is 0.872, which means this study is of great reliability.

B. CORRELATION QUESTIONNAIRE

In this study, the investigation on the correlation between virtual simulation system teaching model and the development of CT adopts questionnaire surveys on the correlation of elements in asynchronous interactive activity. The teaching design framework refers to CT practice model designed by Garrison et al, based on the deviation degree of the virtual simulation system teaching activities and CT, and lays emphasis on promoting the development of CT tendency [54]. Therefore, in the survey of influence degree on CT in the implementing process of the virtual simulation system teaching method, we choose the relevant factors that affect the development of CT tendency, that is, six independent variables, including learning style, learning resources, learning situations, teacher guidance, problem guidance, evaluation and reflection, and each of them has five levels of evaluation, including very great impact, great impact, general impact, very little impact, no impact at all. Likewise, these evaluations were done after having excluded 3 copies of invalid questionnaire, retaining 60 copies valid.

C. OBJECT OF STUDY

In this study, the objects are junior students who major in NC machining in the engineering college of the author's university, and the empirical study on the virtual simulation system teaching activities promoting the development of CT dispositions were experimented on those 63 college students. The investigation is carried out in two ways. One is to send the questionnaire to the subject via the network communication software such as QQ, and the second is to issue and fill in the field questionnaire to the class in which the subject is located.

D. DATA ANALYSIS

The data of CCTDI and the correlation questionnaire were counted and analyzed by SPSS20.0. Through the comparative analysis of the data changes of a CT disposition in college students, it is verified that the virtual simulation system teaching method could promote the development of the students' CT ability. Descriptive statistics were employed to figure out the overall situation of CT dispositions on subject before and after test, and the paired sample t-test was used to analyze whether there is a significant difference between subjects on CT, before and after the virtual simulation system teaching activities. To analyze questionnaire on the influence of basic elements of design framework on CT dispositions, multiple linear regression model was adopted.

V. RESULTS AND DISCUSSION

A. TOTAL SCALE ANALYSIS OF STUDENTS' CRITICAL THINKING DISPOSITION BASED ON THE PRETEST AND POSTTEST

The research adopts one-group pretest-posttest design to infer the learning performance from the pre-education and posttest results. The frequency of the total score in 280-350 of the pretest and posttest was 40% and 78%, respectively. The coefficient of skewness of the pretest and posttest was 0.153 and −0.207, respectively. The Kolmogorov-Smirnova statistical data of the total score of the pretest and posttest was 0.075 and 0.083 respectively, and the significance probability values were all $p = 0.200 > 0.05$, indicating that the total scores of the pretest and posttest were observed in a normal distribution. As shown in Table 2, the highest score of students in the pretest effective data was 319 points, the lowest score was 237 points; the highest score of students in the

TABLE 3. The paired sample test.

		t	df	Sig
Paired 1	Total score of pretest and posttest	-21.785	59	0.000

TABLE 4. Subscale statistics of students' CT dispositions based on the pretest and posttest.

		N	Minimum value	Maximum value	Mean value	Standard deviation
Truth seeking	Pretest statistics	60	30.00	54.00	39.500	5.30909
	Posttest statistics	60	43.00	57.00	49.5333	3.26495
Open-mindedness	Pretest statistics	60	29.00	47.00	37.1667	4.48790
	Posttest statistics	60	42.00	56.00	49.0500	3.31624
Analytical ability	Pretest statistics	60	29.00	56.00	40.7333	5.65945
	Posttest statistics	60	39.00	55.00	47.7833	3.81385
Systematic ability	Pretest statistics	60	31.00	51.00	40.9000	5.40151
	Posttest statistics	60	39.00	56.00	49.1167	3.41528
Self-confidence	Pretest statistics	60	23.00	51.00	39.4000	6.55666
	Posttest statistics	60	39.00	57.00	49.5833	3.82805
Intellectual curiosity	Pretest statistics	60	28.00	51.00	40.4833	5.84109
	Posttest statistics	60	39.00	58.00	48.4667	4.63760
Cognitive maturity	Pretest statistics	60	29.00	53.00	41.7000	5.16606
	Posttest statistics	60	39.00	56.00	47.9667	4.37236

posttest effective data was 371 points, the lowest score was 315 points; The mean values of the pretest and posttest were 279.6 and 341.5, indicating that the overall level of the students had a certain improvement and the majority of the test levels were in the neutral range.

In Table 3, the paired sample test results show that the parameter p is less than 0.05, which means to reject the null hypothesis of the paired t-test, indicating that there were significant differences between the total scores of the pretest and posttest, and the mean value of the posttest is higher than the pretest mean. It is demonstrated that the virtual simulation system teaching method has a positive effect on the development of students' CT dispositions.

B. SUNSCALE ANALYSIS OF STUDENTS' CRITICAL THINKING DISPOSITION BASED ON THE PRETEST AND POSTTEST

As shown in Table 4, the mean values of 5 scales, including truth seeking, open-mindedness, systematic ability, self-confidence and intellectual curiosity, had increased by more than 8 points, and the promotion effect of the cognitive maturity was not too obvious. The frequency of the subscale over 50 points in the posttest process, which involves the open-mindedness, truth seeking, intellectual curiosity and self-confidence, had increased.

The paired sample t-test results of 7 subscales of CT dispositions in the pretest and posttest process (Table 5) showed that for truth seeking (T1-T2), $t = -11.873$, $p = 0.000146 < 0.05$; for open-mindedness (O1-O2), $t = -15.746$, $p = 0.002 < 0.05$; for analytical ability (A1-A2), $t = -7.831$, $p = 0.007 < 0.05$; for systematic ability (S1-S2), $t = -9.532$, $p = 0.00029 < 0.05$; for self-confidence (C1-C2), $t = -10.083$, $p = 0.000034 < 0.05$, for intellectual curiosity (I1-I2), $t = -8.388$, $p = 0.034 < 0.05$. The statistics of t-test are significant, which indicates that all the subscales have correlation, and the virtual simulation system teaching method has a certain influence on the various dimensions of CT dispositions. The comprehensive mean values of truth seeking, open-mindedness, systematic ability, analytical ability, self-confidence and intellectual curiosity in two tests are significantly different, which indicates that learners' promotion in six dimensions of CT dispositions is more obvious.

C. CORRELATION BETWEEN VIRTUAL SIMULATION SYSTEM TEACHING ACTIVITIES AND CRITICAL THINKING DISPOSITION

Multiple linear regression (stepwise) analysis shows that six variables of virtual simulation system teaching method include the learning style, learning resources, learning situations, teacher guidance, problem guidance, evaluation and

TABLE 5. Subscale statistics of the paired sample test.

		Mean value	Standard deviation	t	df	Sig
Paired 1	T1-T2	-10.033	6.74	-11.873	59	.000146
Paired 2	O1-O2	-11.8833	5.84573	-15.746	59	.002
Paired 3	A1-A2	-7.0503	6.97313	-7.831	59	.007
Paired 4	S1-S2	-8.2167	6.67678	-9.532	59	.000029
Paired 5	C1-C2	-10.1833	7.82324	-10.083	59	.000034
Paired 6	I1-I2	-7.9834	7.37263	-8.388	59	.034
Paired 7	M1-M2	-6.2667	7.42389	-6.539	59	.34

TABLE 6. Regression analysis of related variables and CT dispositions.

Model	Unstandardized Coefficients		Standardized Coefficients	T	Sig
	B	Std. Error	Beta		
Constant	8.196	1.822		4.500	0.000
learning style	0.851	0.196	0.383	4.344	0.000
learning resources	0.816	0.199	0.351	4.108	0.000
learning situations	0.881	0.211	0.365	4.175	0.000
teacher guidance	0.686	0.206	0.292	3.336	0.002
problem guidance	0.684	0.246	0.263	2.783	0.007
evaluation and reflection	0.677	0.289	0.223	2.344	0.023

reflection, which are more significant in the design framework, as shown in Table 6. All of these prove that all variables of virtual simulation system teaching method predict that the correlation between the posttest score and CT dispositions is higher. Through the practical learning in the virtual simulation environment, the students generally think that the virtual simulation system teaching method has a strong influence on their CT ability.

D. IMPLICATIONS OF THE RESEARCH RESULTS

On the basis of previous research, this article constructs a framework for learning activities of the virtual simulation system teaching method, which aims at cultivating students' CT ability, and validates the effectiveness of the learning framework through data analysis.

First, the difference between the pretest and posttest verified the validity of the learning framework in promoting the development of the students' CT. From the results of the empirical analysis, the overall mean of the students' CT ability has been improved, and they are moving towards the neutral and stronger areas. At the same time, the improvement effect of the analytical ability and system capability in the subscale is more significant, and the number of people who have an open mind and a strong desire for knowledge have increased, which shows that the learning framework of the virtual simulation system teaching method has a certain effect on the cultivation of students' CT.

Second, the students' externalized interaction activities in teaching process are related to their internalized thinking activities. Considering that the correlation between the learning style and learning situations of the virtual simulation system teaching method and CT development is relatively higher, therefore, how to set up effective teaching situations and teaching styles in the implementing process of the virtual simulation system teaching method has been proved to be the key link to improve the students' CT ability. In the process of designing the virtual simulation system teaching activities, we should attach importance to the role of teaching situation and teaching style, and promote the improvement of each tendency dimension of CT by using a variety of virtual simulation interaction activities.

E. COMPLIANCE WITH ETHICAL STANDARDS

The authors declare that they have no conflict of interest. Informed consent was obtained from all individual participants included in the study. All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

VI. CONCLUSION

It is a significant task for higher education to promote the development of creative thinking ability of college students, and cultivate innovative talents with creative consciousness, spirit and ability, which needs effective measures taken by colleges and universities. The task of teaching in higher education is not only to let students master the subject knowledge, but also to enable students to understand their own thinking content, so that they could be familiar with their own thinking mode and then learn to control their thinking process. To explore the training mode and approach of innovative talents, it urgently needs the theoretical and empirical research on the core elements of innovative talents-CT.

This article proposes ways to understand and study Chinese students not previously considered in CT literature. It applies the virtual simulation system teaching method in NC teaching, through the secondary development technology of the software UG completely, to let the students learn to establish their own NC machining simulation system, which can combine the complex knowledge points involved in NC machining, and presents them to the students in a simple, quick and easy way. Meanwhile, it also exposes the students to CT principles and skills implicitly, through immersing themselves in thought-provoking subject matters. The combination of theoretical inquiry and empirical research shows that the virtual simulation system teaching method has obvious improvement on the cultivation of the students' CT. It helps students to enhance their learning interest and have a wider range of knowledge, so as to master NC professional knowledge in depth and improve their comprehensive innovation ability. Moreover, it is emphasized for the engineering students to enhance practical ability while learning the theoretical knowledge. Fortunately, the open and innovative virtual learning environment provided by virtual simulation system is favorable to achieve this teaching goal.

Although the virtual simulation system teaching method proposed in this article has shown great advantages in the actual teaching process, it can not completely replace the practical training in reality. Because the students are not personally involved in the hands-on operation training, it affects the students' practical operation skills. The effective CT teaching strategies should expose the students to authentic or situated problems and examples in NC machining. Therefore, the future research direction of this article would focus on how to combine virtual simulation with practical training to realize their complementary advantages, aiming to explore an appropriate way of promoting the students' all-round development.

REFERENCES

[1] V. N. Lunnetta, A. Hofstein, and M. P. Clough, "Learning and teaching in the school science laboratory: An analysis of research, theory and practice," in *Handbook of Research on Science Education*, S. K. Abell and N. G. Lederman, Eds. Mahwah, NJ, USA: Lawrence Erlbaum Associates, Jan. 2007, ch. 15, pp. 393–441.

[2] R. E. Slavin, *Educational Psychology: Theory and Practice*, 4th ed. Boston, MA, USA: Allyn and Bacon, 1994.

[3] H. Aktamä and N. Yenice, "Determination of the science process skills and critical thinking skill levels," *Procedia—Social Behav. Sci.*, vol. 2, no. 2, pp. 3282–3288, 2010.

[4] A. Ahern, "A literature review of critical thinking in engineering education," *Stud. Higher Educ.*, vol. 5, pp. 816–828, May 2019.

[5] C. Lionel and R. Donna, "Situation critical: Critical theory and critical thinking in engineering education," *IEEE Women Eng. Mag.*, vol. 1, no. 1, pp. 32–36, Jun. 2013.

[6] P. Crenshaw, E. Hale, and S. Harper, "Producing intellectual labor in the classroom: The utilization of a critical thinking model to help students take command of their thinking," *J. College Teach. Learn.*, vol. 7, pp. 13–26, Jul. 2011.

[7] T. Moore, "Critical thinking: Seven definitions in search of a concept," *Stud. Higher Edu.*, vol. 38, no. 4, pp. 506–522, May 2013.

[8] K. Y. L. Ku, "Assessing students' critical thinking performance: Urging for measurements using multi-response format," *Thinking Skills Creativity*, vol. 4, no. 1, pp. 70–76, Apr. 2009.

[9] A. Heijltjes, T. van Gog, J. Leppink, and F. Paas, "Improving critical thinking: Effects of dispositions and instructions on economics students' reasoning skills," *Learn. Instruct.*, vol. 29, pp. 31–42, Feb. 2014.

[10] C.-K. Cheung and A. D. Jhaveri, "Developing students' critical thinking skills through visual literacy in the new secondary school curriculum in hong kong," *Asia Pacific J. Edu.*, vol. 36, no. 3, pp. 379–389, Jul. 2016.

[11] O. Korkmaz and U. Karakus, "The impact of blended learning model on student attitudes towards geography course and their critical thinking dispositions and levels," *Turkish Online J. Educ. Technol.*, vol. 8, pp. 51–63, Oct. 2014.

[12] L. O'Keeffe and J. O'Donoghue, "A role for language analysis in mathematics textbook analysis," *Int. J. Sci. Math. Edu.*, vol. 13, no. 3, pp. 605–630, Jun. 2015.

[13] O. L. Liu, L. Y. Mao, and L. Frankel, "Assessing critical thinking in higher education: The HEIghten approach and preliminary validity evidence," *Assessment Eval. Higher Educ.*, vol. 41, pp. 677–694, Jul. 2016.

[14] M. J. Bezanilla, "Methodologies for teaching-learning critical thinking in higher education: The teacher's view," *Thinking Skills Creativity*, vol. 33, pp. 1–10, Sep. 2019.

[15] S. A. Forawi, "Standard-based science education and critical thinking," *Thinking Skills Creativity*, vol. 20, pp. 52–62, Jun. 2016.

[16] R. D. Liu, "The comment on the meaning and connotation of critical thinking," *Teacher Educ. Res.*, vol. 12, pp. 56–61, Apr. 2000.

[17] S. Cargas, S. Williams, and M. Rosenberg, "An approach to teaching critical thinking across disciplines using performance tasks with a common rubric," *Thinking Skills Creativity*, vol. 26, pp. 24–37, Dec. 2017.

[18] M. Battersby and S. Bailin, "Critical inquiry: Considering the context," *Argumentation*, vol. 25, no. 2, pp. 243–253, May 2011.

[19] R. T. Pithers and R. Soden, "Critical thinking in education: A review," *Educ. Res.*, vol. 42, pp. 237–249, Jan. 2000.

[20] X. F. Zhang, "The application study of critical thinking teaching method," *Softw. Guide Educ. Technol.*, vol. 9, pp. 64–65, Apr. 2015.

[21] J. H. Yang and L. Han, "A study on the cultivation of critical thinking ability in the reform of foreign language teaching," *Academic Forum*, vol. 4, pp. 198–200, May 2006.

[22] H. David, "Critical thinking as an educational ideal," *J. Higher Educ.*, vol. 33, pp. 54–63, Nov. 2012.

[23] Z. D. Liu, "Application of virtual simulation technology in engineering training," *Res. Explor. Lab.*, vol. 36, pp. 160–163, May 2017.

[24] I. Jawaid, M. Y. Javed, M. H. Jaffery, A. Akram, U. Safder, and S. Hassan, "Robotic system education for young children by collaborative–project–based learning," *Comput. Appl. Eng. Edu.*, vol. 28, no. 1, pp. 178–192, Jan. 2020.

[25] X. J. Duan, "System teaching method and its application in curriculum reform," *Vocational Educ. Res.*, vol. 7, pp. 128–130, Dec. 2009.

[26] D. T. Tiruneh, "Systematic design of a learning environment for domain-specific and domain-general critical thinking skills," *ETR D-Educ. Technol. Res. Develop.*, vol. 64, pp. 1–25, May 2015.

[27] J. J. Huang, "Cultivation of college students in the twenty first century: Fusion of general education and specialty education," *Peking Univ. Educ. Rev.*, vol. 4, pp. 19–28, Mar. 2006.

[28] S. A. Kocadere and D. Ozgen, "Assessment of basic design course in terms of constructivist learning theory," *Procedia—Social Behav. Sci.*, vol. 51, pp. 115–119, May 2012.

[29] N. Alalwan, W. M. Al-Rahmi, O. Alfarraj, A. Alzahrani, N. Yahaya, and A. M. Al-Rahmi, "Integrated three theories to develop a model of factors affecting Students' academic performance in higher education," *IEEE Access*, vol. 7, pp. 98725–98742, 2019.

[30] Y. W. Kwan and A. F. L. Wong, "Effects of the constructivist learning environment on students' critical thinking ability: Cognitive and motivational variables as mediators," *Int. J. Educ. Res.*, vol. 70, pp. 68–79, Aug. 2015.

[31] B. G. Wilson, *Constructivist Learning Environments: Case Studies in Instructional Design*. Englewood Cliffs, NJ, USA: Educational Technology, 1996.

[32] Y. Yao, J. Li, and C. Liu, "A virtual machining based training system for numerically controlled machining," *Comput. Appl. Eng. Edu.*, vol. 15, no. 1, pp. 64–72, 2007.

[33] L. S. Melanie, A. V. Peter, and L. H. Katherine, "Active learning in flipped life science courses promotes development of critical thinking skills," *CBE-Life Sci. Educ.*, vol. 39, pp. 1–13, Mar. 2018.

[34] L. M. Michaluk, J. Martens, and L. Rebecca, "Developing a methodology for teaching and evaluating critical thinking skills in first-year engineering students," *Int. J. Eng. Educ.*, vol. 32, pp. 84–99, Jan. 2016.

[35] M. Priyaadharshini and B. Vinayaga Sundaram, "Evaluation of higher-order thinking skills using learning style in an undergraduate engineering in flipped classroom," *Comput. Appl. Eng. Edu.*, vol. 26, no. 6, pp. 2237–2254, Nov. 2018.

[36] J. Redoli, M. Rafael, D. D. Lamata, and M. Doctor, "DLP: A tool to develop technical and soft skills in engineering," *Comput. Appl. Eng. Educ.*, vol. 21, pp. 51–61, Aug. 2013.

[37] E.-S. Aziz, "Teaching and learning enhancement in undergraduate machine dynamics," *Comput. Appl. Eng. Edu.*, vol. 19, no. 2, pp. 244–255, Jun. 2011.

[38] S. M. Danczak, C. D. Thompson, and T. L. Overton, "Development and validation of an instrument to measure undergraduate chemistry students' critical thinking skills," *Chem. Edu. Res. Pract.*, vol. 21, no. 1, pp. 62–78, Jan. 2020.

[39] S. Scott, "Perceptions of students' learning critical thinking through debate in a technology classroom: A case study," *J. Technol. Stud.*, vol. 1, pp. 39–44, Apr. 2008.

[40] S. A. Forawi and R. M. Mitchell, "Preservice teachers' perceptions of critical thinking attributes of the Ohio and New York states' science and math content standards," *J. Teach. Educ.*, vol. 5, pp. 379–388, May 2012.

[41] L. M. Yao, "Research and enlightenment of foreign teaching to promote the development of college students' critical thinking," *Higher Educ. Sci.*, vol. 5, pp. 18–21, May 2001.

[42] R. Duron, B. Limbach, and W. Waugh, "Critical thinking framework for any discipline," *Int. J. Teach. Learn. Higher Educ.*, vol. 2, pp. 160–166, Apr. 2006.

[43] S. Veronika, Z. Roman, and A. Stanislav, "Interdisciplinary critical and design thinking," *Int. J. Eng. Educ.*, vol. 1, pp. 84–95, Dec. 2020.

[44] Y. Li, D. Zhang, H. Guo, and J. Shen, "A novel virtual simulation teaching system for numerically controlled machining," *Int. J. Mech. Eng. Edu.*, vol. 46, no. 1, pp. 64–82, Jan. 2018.

[45] T. C. Hutchinson and F. Kuester, "Hardware architecture for a visualization classroom: VizClass," *Comput. Appl. Eng. Edu.*, vol. 12, no. 4, pp. 232–241, 2004.

[46] Y. X. Li, "Research and application of the virtual simulation system teaching method in NC machining course," *Simul., Sci. Comput.*, vol. 9, Feb. 2018, Art. no. 1850007.

[47] C.-F. Chau and Y.-F. Fung, "A tool for self-learning assembly language programming and computer architecture: Design and evaluation," *Comput. Appl. Eng. Edu.*, vol. 19, no. 2, pp. 286–293, Jun. 2011.

[48] J. L. Sanchez-Romero, A. Jimeno-Morenilla, M. L. Pertegal-Felices, and H. Mora-Mora, "Design and application of project-based learning methodologies for small groups within computer fundamentals subjects," *IEEE Access*, vol. 7, pp. 12456–12466, 2019.

[49] M. Manso-Vazquez, M. Caeiro-Rodriguez, and M. Llamas-Nistal, "An xAPI application profile to monitor self-regulated learning strategies," *IEEE Access*, vol. 6, pp. 42467–42481, 2018.

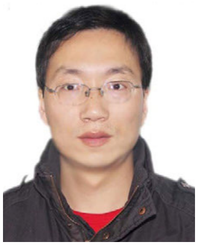
[50] M. Li, Y. Li, and H. Guo, "Research and application of situated teaching design for NC machining course based on virtual simulation technology," *Comput. Appl. Eng. Edu.*, vol. 28, no. 3, pp. 658–674, May 2020.

[51] D. K. Glopper, A. Fisher, and M. Scriven, "Critical thinking. Its definition and assessment," *Argumentation*, vol. 16, pp. 247–251, May 1997.

[52] R. H. Johnson and B. Hamby, "A meta-level approach to the problem of defining–critical thinking," *Argumentation*, vol. 29, no. 4, pp. 417–430, Nov. 2015.

[53] C. Perkins and E. Murphy, "Identifying and measuring individual engagement in critical thinking in online discussions: An exploratory case study," *Educ. Technol. Soc.*, vol. 9, May 2006, pp. 298–307.

[54] D. R. Garrison, T. Anderson, and W. Archer, "Critical thinking, cognitive presence, and computer conferencing in distance education," *Amer. J. Distance Edu.*, vol. 15, no. 1, pp. 7–23, Jan. 2001.



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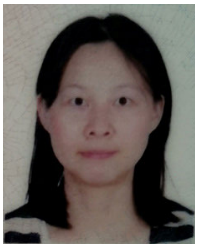

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