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Enhancing mechanisms education through interaction with augmented reality simulation

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Abstract

Computer simulation has been used pervasively to help students understand deeply and visually the theoretical bases of mechanisms. This paper proposes an AR mechanism education system (ARMES) to provide a tool that can conduct mechanism simulations with high level of interaction, easy modeling, and simulation environment and working on real mechanisms. The system consists of theoretical lecture mode and practical exercise mode. Theoretical lecture mode adopts the basic theories of mechanisms from the book *Mechanisms and Machine Theory* (MMT) and provides an interactive learning style for users via an interactive tool. Practical exercise mode allows modeling, simulation, kinematical characteristics analysis, dynamic analysis, and synthesis based on the interaction with the information that has been rendered on a real mechanism via the interaction tool. In addition, the modeling is based on markers, making the system easy for novice learners to use. The simulation is based on geometrical concepts, making the geometrical bases of mechanism theories clear for users to understand. The evaluation of the system is conducted with 20 participants and a survey. The results reveal that by exploiting the characteristics of AR, the system is helpful in improving the interaction, visualization, and practicality of the mechanism problems. These features will make the system a powerful tool for the teaching of mechanisms.

KEYWORDS

augmented reality, interaction, mechanism, modeling, simulation

1 | INTRODUCTION

Most machines, even very complicated ones, are built up from only a few types of commonly used mechanisms, such as linkages, gears, cam mechanisms, etc. The functions and profiles of machines may be quite different, but the mechanisms used in them are often the same [30]. Learning how to design them is the basic requirement for mechanical students in universities. They are covered in the course *Mechanisms and Machine Theory* (MMT) [9], which is one of the important technical foundation courses for mechanical students in universities. Subjects, such as mathematics, physics, perspective geometry, theoretical mechanics, and engineering graphics are integrated in this course. Hence, a large amount of information and a high level of difficulty of the content are the challenges faced in the study or teaching of linkage mechanisms [12].

Computer technologies are providing unique insights into the way the world works today. Students can now experiment real problem solving tasks in a virtual world of complex, dynamic systems in a way that was impossible before [23]. The education of mechanisms has also been enhanced by the modern trend due to the wide use of computer technologies. Computer simulation and analysis software has been used pervasively to help students understand deeply and visually the theoretical bases, and the kinematic and dynamic characteristics of the mechanisms [15]. One example is the use of commercial software packages, such as ADAMS [1] or LMS Virtual.Lab [14]. These kinds of general-purpose programs have the advantages due to their powerful capabilities and their reliability. However, it is necessary to spend a considerable amount of time to train the students in the use of these programs, which have been developed to be used by technicians and experts [21]. The other alternative is educational computer software that allows the modeling of mechanisms in an easier and simpler way as compared with the commercial software packages, such as GIM [8], MechAnalyzer [19], SAM [22], etc. The main function of these software is to compute different theoretical entities that characterize the kinematic behaviors of a mechanism [9,21]. Although such software provides an innovative means for the study of mechanisms, there are still limitations, such as limited interaction with users, complex modeling process, and neglect of practice with real mechanisms. All these limitations should be improved to provide a better interaction, which can transform students from passive to active learners; an easy modeling environment is very effective for novice learners and practice with real mechanisms can provide a lucid process to enhance the understanding of the theories. To overcome these shortcomings, the development of new methods and systems, based on the mixing of the real world and the virtual objects, appears to be the future of computer-aided studies. One of these instruments is Augmented Reality (AR) [26].

AR enriches the way that users experience the real world by embedding virtual objects to coexist and interact with real objects in the real world [27]. It is characterized by the following three properties: (1) combining real and virtual objects in a real environment; (2) aligning real and virtual objects with each other; and (3) operating interactively and in real time [2]. These characteristic benefits enable educators and designers to superimpose virtual graphics over real objects, allowing users to interact with digital content via physical manipulation [29]. Therefore, AR could provide intuitive interaction between the users and the simulated system and allow a more appealing visualization of simulation results. For these reasons, simulation with AR has been found to most apt for didactical applications and teaching purposes [18].

In this paper, an AR mechanism education system (ARMES) is proposed. It uses a mixture of physical objects and virtual graphics to allow students to appreciate a high level of interaction with the augmented study content intuitively, understand the kinematics and dynamic behavior of mechanisms by moving the real mechanism to update the augmented information, and enhance the study efficiency under appropriate guidance provided by augmented scene. The rest of the paper is organized as follows. Section 2 presents the related studies on AR applications in education and simulation in AR environment. Section 3 gives an overview of the system architecture, Section 4 and section 5 present the details of the proposed system. Section 6 describes the evaluation of the system. Section 7 summarizes the study and presents the future work.

2 | RELATED WORK

2.1 | AR applications in education

Scientific literature reports an increasing interest for the development of AR applications in the education field. AR has been successfully implemented in various teaching and learning domains, such as medicine, biology, mechanical engineering, electromagnetism, and geometry [5,10,20,24,25].

Thomas et al. [25] developed an AR education tool to teach medical students about human anatomy. A user can view the head and the ventricles at his or her own pace, explore the head by moving a tracked model of the same ventricle data that is being viewed onscreen, and interrogate this data using a tracked tool held in the other hand. The result of their user study reveals that novel viewing features based on AR can make it an effective learning aid. Another advantage is that this system can be used at any time. In contrast, time in traditional dissection room is scarce and subject to the availability of a cadaver.

Tarng and Ou [24] used AR to design a virtual butterfly ecological environment. Students can breed virtual caterpillars on host plants using smart phones, and become familiar with a butterfly's life cycle by observing their growth. The idea of learning by playing enhances students’ learning motivation and interest. Compared with real butterfly gardens, the AR butterfly ecological environment is easy to develop and maintain, and it can solve the problem of insufficient species and amount of butterflies. In addition, the system is not limited by time or space. Students can learn in their familiar environment, making the situated cognition more concrete.

Monroy Reyes et al. [20] developed an AR system to support risky machinery operations in academic manufacturing environments. The system was designed to guide unexperienced students in the use of machinery, by providing them with virtual information while handling a lathe and a milling machine in a university laboratory. The test results revealed that the system is well accepted and AR is a valuable tool to augment a particular operation with interactive virtual models.

Ibáñez et al. [10] developed an AR-based application for learning the basic principles of electromagnetism. Tangible elements tagged with a fiducial marker are used to mimic circuit elements. After constructing a physical paper circuit using these elements, the students were allowed to visualize the electric fields, the magnetic fields and the movement of the current-carrying wires in different stages with respect to different batteries and magnets, respectively using the application. A comparison experiment with a web-based learning application showed that the AR approach was more effective in promoting students' knowledge of electromagnetic concepts and phenomena. The analysis also indicated that the AR application could enable participants to reach higher flow experience levels.

Chen et al. [5] developed an AR teaching aid to help students better understand the relationships between 3D objects and their projections. AR virtual models of 3D graphics of typical geometries can be superimposed on real-time video and vary view perspective dynamically in real-time. The virtual models include all the geometrical features generally taught in engineering graphics courses or technical drawing courses. The user tests indicated that the interests of students in engineering graphics courses are enhanced and it is an effective teaching aid.

All these systems have proved that educational content can be comprehended better and faster using AR. As for the education of mechanisms, there are also some attempts based on AR. Sidhu et al. [16,17,23] developed a few AR systems for the interactive study of linkage mechanisms. In one system, they developed an interactive AR book using markers for the study of four-bar linkages. Using a PC-Camera, students can find 3D virtual models that pop up over the book and they can interact with the virtual models by controlling their animations. In another system, markers are used as learning-aided cues in an AR environment to enhance the learning process of crank slider mechanisms. Students can use these cues to change the color of the mechanisms, display 3D models, 2D diagrams, axes, and motion trail/path. In their recent system, a new interactive book on four-bar linkages was designed based on their first system. The interaction with the book was simplified and the touch interaction with the virtual models was adopted. Users can change the length of the links of the virtual model, obtain analytical information, such as the rotation angle of each link, and start or stop the rotation of the virtual model at any time to study the status of the current model. These systems have provided interesting tools for the education of mechanisms although there are still some limitations that can be enhanced. An important issue that has been neglected in these systems is the practice with real mechanisms. Practice with real mechanisms will give students a clear understanding of the mechanism theory and an effective method to benefit from the transfer of basics to practical examples. Thus, just presenting the theory and analytical results and controlling the simulation of virtual models are not sufficient for a comprehensive education system of mechanisms. In addition, the virtual models in these systems are predefined, lacking of function of building the virtual model of a mechanism by students. Modeling by the students will not only enhance their understanding, but also make the analysis and synthesis of a real mechanism easier for the students. The research in this paper will focus on filling these gaps.

2.2 | Simulation in AR environment

Interactive computer simulations have properties that can effectively facilitate learning and engagement in science [4]. The technology of AR, which combines virtual and physical elements to develop a more immersive environment, allows users to interact with simulations in more natural and physically expressive ways [13]. Many researches have reported such applications of AR simulation.

Zhang et al. [31] developed an AR CNC machining simulation system. A virtual workpiece is rendered onto the worktable of a real CNC machine, and a virtual cutter is registered with the real cutter moving according to given NC codes. The system provides machining simulation on real CNC machines so that the user can acquire the knowledge of the specific CNC machines intuitively. It can be used to train novice machinists and observe machining simulation before the actual machining operations.

Coles et al. [6] developed an AR simulation system for training femoral palpation and needle insertion. It allows the trainees to see a computer generated patient and needle, and interacts using their own hands. This simulation provides a high level of face validity.

Fang et al. [7] developed an AR-based system to facilitate robot programming and trajectory planning. Through the various simulation capabilities provided in AR environment, the users are able to preview the simulated motion, perceive any possible overshoot, and resolve discrepancies between the planned and simulated paths prior to the execution of a task. By performing the simulation, the performance of the trajectory planning and the fitness of the selection of the robot controller model/parameters in the robot programming process can be visually evaluated.

Wang et al. [28] developed an assembly simulation system. With this system, users can manipulate and assemble virtual components to real components. The system can facilitate on-site design by simulating all the physically plausible movements between the components throughout the assembly process. The user can assess the difficulty level of assembly operations using bare-hand based on physical interaction with both real and virtual components in the AR environment at the initial stage of a product design.

The literature reviewed proves the benefits of using AR-based simulation. As for the simulation of mechanisms in AR, Valentini et al. [26] developed a methodology for implementing, solving and reviewing multibody simulation. The simulation of a bouncing ball, a spatial manipulator and a slider-crank mechanism were conducted in their work. According to their results, AR facilitates the interaction between the user and the simulation and allows a more appealing visualization of simulation results. Although their work has provided a powerful system for the simulation of mechanism in AR environment, it is not suitable for the education of MMT. The simulation in their work is based on multibody techniques, and the geometrical bases of the mechanism theory are hidden from the students in the mathematical formulation of the kinematic problems [21]. To provide a useful tool for the understanding of the mechanisms theory, the simulation in this paper is based on the geometric method.

3 | SYSTEM OVERVIEW

The courses of MMT are usually divided into two parts, namely, theoretical lectures and practical exercises. While theoretical lectures provide knowledge and necessary theoretical backgrounds, practical exercises illustrate the application of introduced methods and give students the opportunity to complement and reinforce the theoretical lectures [3]. Regarding the course contents of mechanisms, one focus is the analysis procedures for kinematical characteristics and dynamic states, and another important issue is the synthesis of these mechanisms [11]. Therefore, the proposed ARMES is developed with two modes, namely, Theoretical Lecture (TL) mode and Practical Exercise (PE) mode (Figure 1). The TL mode is used for theory learning; it stores the basic theories of mechanisms and provides an interactive learning style for the users via the interactive tool of the book Mechanisms and Machine Theory. The PE mode consists of five modules, namely, Geometrical Modeling (GM) module, Motion Simulation (MS) module, Kinematical Characteristics (KC) module, Dynamic Analysis (DA) module, and Dimensional Synthesis (DS) module. The GM module constructs the virtual geometrical model of a real mechanism interactively based on markers to make it easy for novice learners to use. The MS module simulates the virtual model constructed in the GM module in two ways. The KC and DA modules provide guidance for users to conduct characteristic analysis and dynamic analysis respectively. The DS module provides practical exercises of the synthesis methods of mechanisms. Practical exercises have traditionally relied on real mechanisms; hence, real mechanisms are used as interactive tools in the PE mode. The four-bar linkage, which is one of the common mechanisms, is used as an example to illustrate the proposed framework. Details of each module will be described accordingly.

4 | THEORETICAL LECTURE MODE

Theory topics are mainly graphical; animation is always used to visualize the graphical construction as well as the derivation of theory. Basic theories of the four-bar linkage, including the Grashof criterion, transmission angle, dead center position, etc., are demonstrated interactively and graphically with animation in the TL mode. The Grashof criterion is used as an example to illustrate the TL mode. Details are described as follows.

The book *Mechanisms and Machine Theory* is used as an interactive tool. Students turn the book to the pages of Four-bar Linkages, and the text without any additional technology is shown in Figure 2a. However, if they look at the pages in front of a PC-Camera, they can see a detailed explanation of the Grashof criterion and a virtual four-bar

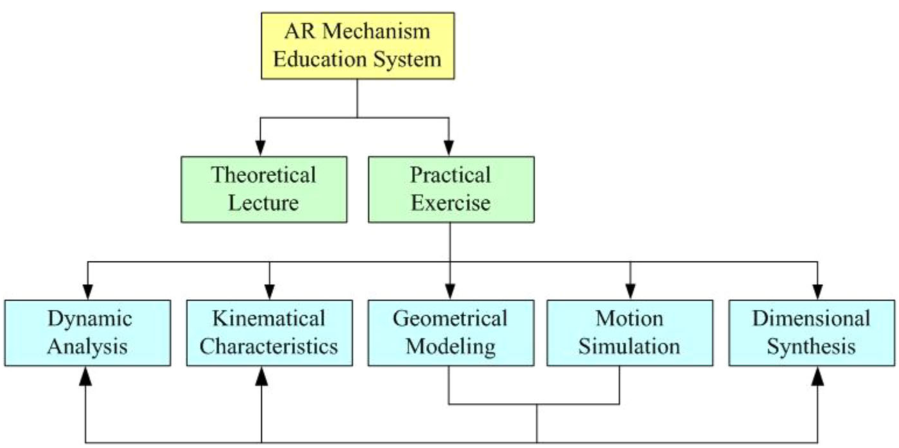
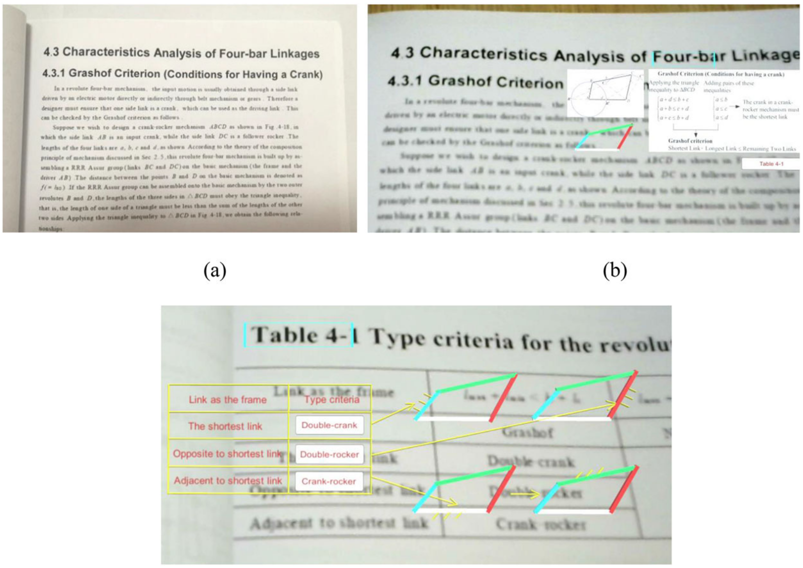


FIGURE 1 Framework of the AR mechanism education system



(a) (b) (c)

FIGURE 2 Three snapshots from theoretical lecture mode (a) book pages, (b) AR scene, and (c) animation

linkage superimposed on the pages as shown in Figure 2b. Students can control the animation of the virtual four-bar linkage to make it pause or replay in any time using the keyboard. The theoretical bases of the Grashof criterion will be understood deeply and visually with the animation of the virtual four-bar linkage. After learning the definition of the Grashof criterion, students can learn other relevant text by pressing the virtual button in the AR scenes, which will guide them easily to find the core content. For example, besides the definition, students need to grasp the classification four-bar linkages based on the use of the Grashof criterion. The book uses almost two pages to explain all the types of four-bar linkages. However, with the help of the proposed system, context-awareness can be easily realized. Students just need to press the button in Table 4–1 in the AR scenes and turn the book to the page which involves Table 4–1, and a table with the names of all the types of four-bar linkages together with their corresponding virtual models will show up, as shown in Figure 2c. Pressing the name of any type of the four-bar linkage in the table, a graphical explanation of this type will appear in the AR scene. Animations of these virtual models attached to the table can also be conducted. In this way, students can distinguish and grasp the differences between these different types easily.

5 | PRACTICAL EXERCISE MODE

A real four-bar linkage, consisting of the crank *AB*, the coupler *BC*, the rocker *CD*, and the frame AD, as shown in Figure 3, is used as interactive tool in the PE mode.

5.1 | Geometrical modeling module

With four markers that are attached to the four pivots of the real four-bar linkage, respectively, as shown in Figure 4a, the position, height and physical length of each link will be computed automatically by recognition of the markers. Next, the virtual geometrical model will be rendered according to the computation results, as shown in Figure 4b.

5.2 | Motion simulation module

For an interactive motion simulation, when a user chooses the position and height of one link, the *AR* scene has to be able to include the right arrangement of other links. In this paper, the crank *AB* is chosen as the reference link. Once the position and height of the crank *AB* are changed, namely, the machine

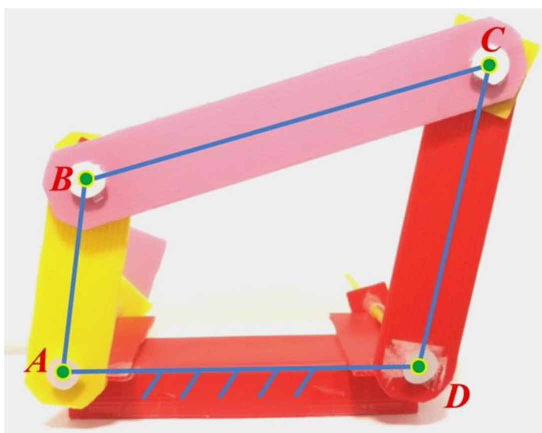
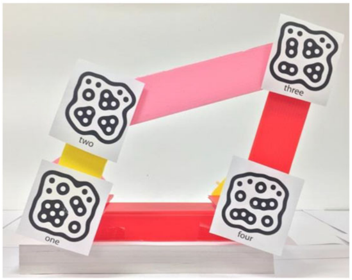


FIGURE 3 Physical four-bar linkage model



(a)

(b)

FIGURE 4 Geometrical modeling in AR environment (a) physical model with makers and (b) rendering the virtual geometrical model

is in motion, the kinematics equations of this mechanism will be solved automatically to compute the correct position of all the virtual links in the AR scene.

5.2.1 | Kinematic equations of four-bar linkage

As shown in Figure 5, a Cartesian coordinate system *X-Y* that is fixed on the pivot *A* is set up. In this case, α_1, α_{21}, and α_{31} represent the rotation angles of the crank AB, coupler *BC* and rocker *CD,* respectively. β represents the angle between line *BD* and the direction of the *X*-axis. The length of the four links are L_1, L_2, L_3, L_4. According to geometrical concepts, Figure 5 yields Equation (1).

$$\overrightarrow{AB} + \overrightarrow{BC} = \overrightarrow{AD} + \overrightarrow{DC} \tag{1}$$

If Equation (1) is transformed into the analytical form, it can be written as the following equation.

$$\begin{cases} x_c = x_B + L_2\cos\alpha_2 = x_D + L_3\cos\alpha_3 \\ y_c = y_B + L_2\sin\alpha_2 = y_D + L_3\sin\alpha_3 \end{cases} \tag{2}$$

where $x_B = L_1\cos\alpha_1, y_B = L_1\sin\alpha_1,\ x_D = L_4,\ y_D = 0.$

In ΔBCD, using the law of cosines, the following equation can be obtained.

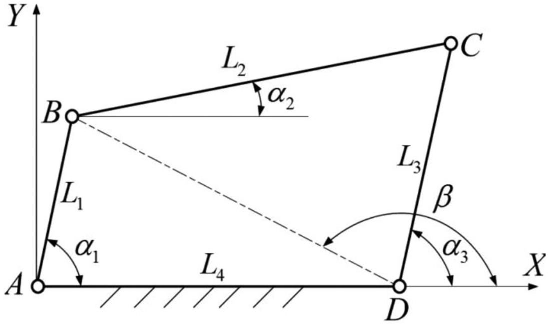


FIGURE 5 Four-bar linkage kinematic diagram

$$\cos(\beta - \alpha_3) = \frac{L_3^2 + (x_B - x_D)^2 + (y_B - y_D)^2 - L_2^2}{2L_3\sqrt{(x_B - x_D)^2 + (y_B - y_D)^2}} \tag{3}$$

where $\beta = \arctan\frac{y_B - y_D}{x_B - x_D}$

Differentiation of both parts of the Equation (2) with respect to time *t* gives Equation (4).

$$\begin{cases} \dot{x}_B - L_2\dot{\alpha}_2\sin\alpha_2 = -L_3\dot{\alpha}_3\sin\alpha_3 \\ \dot{y}_B + L_2\dot{\alpha}_2\cos\alpha_2 = L_3\dot{\alpha}_3\cos\alpha_3 \end{cases} \tag{4}$$

where, $\dot{x}_B = -L_1\dot{\alpha}_1\sin\alpha_1,\ \dot{y}_B = L_1\dot{\alpha}_1\cos\alpha_1$

Equation (4) yields

$$\dot{\alpha}_2 = \frac{\dot{x}_B\cos\alpha_3 + \dot{y}_B\sin\alpha_3}{L_2\ \sin(\alpha_2 - \alpha_3)} \tag{5}$$

$$\dot{\alpha}_3 = \frac{\dot{x}_B\cos\alpha_2 + \dot{y}_B\sin\alpha_2}{L_3\ \sin(\alpha_2 - \alpha_3)} \tag{6}$$

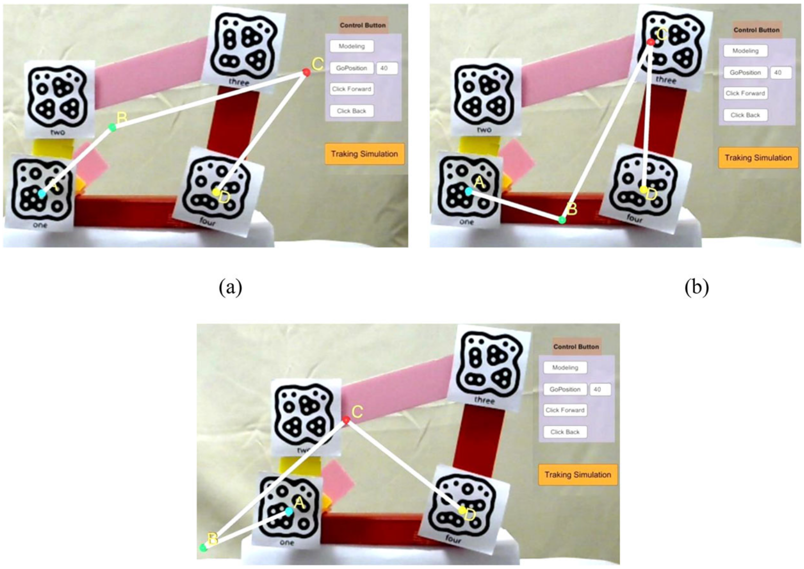
Differentiation of both parts of the Equation (4) with respect to time *t* gives

$$\begin{cases} \ddot{x}_B - L_2\ddot{\alpha}_2\sin\alpha_2 - L_2\dot{\alpha}_2^2\cos\alpha_2 = -L_3\ddot{\alpha}_3\sin\alpha_3 - L_3\dot{\alpha}_3^2\cos\alpha_3 \\ \ddot{y}_B + L_2\ddot{\alpha}_2\cos\alpha_2 - L_2\dot{\alpha}_2^2\sin\alpha_2 = L_3\ddot{\alpha}_3\cos\alpha_3 - L_3\dot{\alpha}_3^2\sin\alpha_3 \end{cases} \tag{7}$$

Equation (7) yields

$$\ddot{\alpha}_2 = \frac{C_1\cos\alpha_3 + C_2\sin\alpha_3}{L_2\ \sin(\alpha_2 - \alpha_3)} \tag{8}$$

$$\ddot{\alpha}_3 = \frac{C_1\cos\alpha_2 + C_2\sin\alpha_2}{L_3\sin(\alpha_2 - \alpha_3)} \tag{9}$$



(a)

(b)

(c)

FIGURE 6 Three snapshots from motion simulation in AR environment in the first mode (a) designated position, (b) clicking forward, and (c) clicking back

where $C_1 = \ddot{x}_B + L_3\dot{\alpha}_3^2\cos\alpha_3 - L_2\dot{\alpha}_2^2\cos\alpha_2,\ C_2 = \ddot{y}_B + L_3\dot{\alpha}_3^2\sin\alpha_3 - L_2\dot{\alpha}_2^2\sin\alpha_2$

Once the position and height of the crank AB is determined, namely, the coordinate values of point B (x_B, y_B) and the value of α_1 in Equation (2) are both known, the value of α_3 can be obtained by substituting these values into Equation (3). Substituting the value of α_3 into Equation (2), the coordinate of the point C $(x_c, y_{c)}$ together with the value of α_2 can be calculated. Finally, from Equations (5–9), the angular velocities of coupler BC $(\dot{\alpha}_2)$ and rocker CD $(\dot{\alpha}_3)$ together with the angular accelerations of coupler BC $(\ddot{\alpha}_2)$ and rocker CD $(\ddot{\alpha}_3)$ can be obtained. Hence, the position, height, velocity and acceleration of all the links are calculated based on geometrical concepts.

5.2.2 | Motion simulation in AR environment

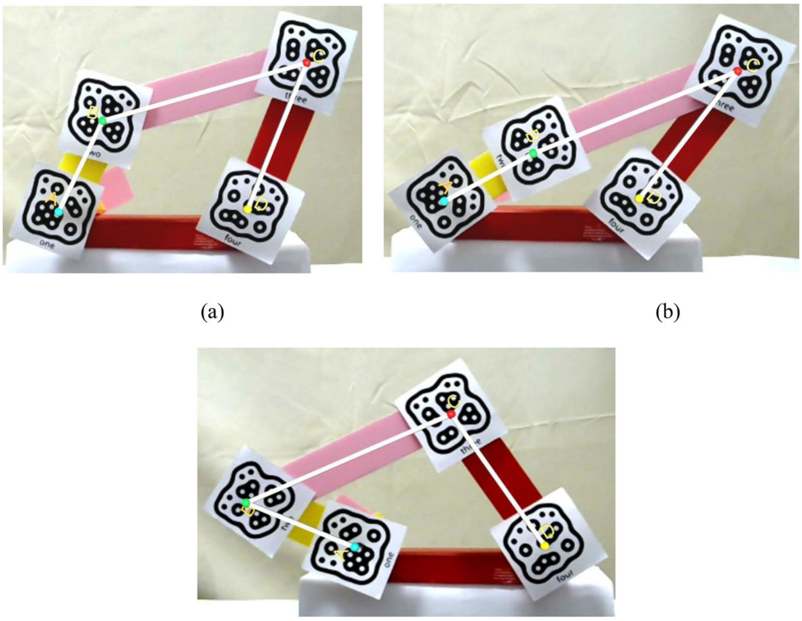
The virtual model is used to conduct motion simulation. The motion simulation is designed in two modes. In the first mode, the actual mechanism is kept motionless; the virtual model is driven by inputting a new position of the crank AB or pressing the button in the AR scene to move the crank gradually, as shown in Figure 6a–c. In the second mode, once the machine is in motion, the virtual model of the mechanism will be updated in the AR scene according to the new position of all links, as shown in Figure 7a–c. In these scenes, once the position and height of crank AB is changed, the kinematics equations will be solved to update the position and height of other links. The system also supports rendering of real-time results of motion simulation for the students. As shown in Figure 8, the rotation angles of all the links are rendered in the AR scene and updated with the motion of the mechanism; the displacement, velocity and acceleration curves of the coupler BC can also be rendered in graphs in the AR scene.

5.3 | Kinematical characteristics module

Kinematical characteristics of the real mechanism are analyzed in the KC module interactively, reinforcing the understanding of the theoretical knowledge. For a four-bar linkage, kinematical characteristics include transmission angle, dead center position, quick return characteristic, etc. To illustrate the KC module, the Quick return characteristic is used as an example.

5.3.1 | Theoretical background of quick return characteristic

In the four-bar linkage shown in Figure 9, C_1DC_2 is called the angular stroke of the rocker, denoted as $\varphi_{\max}$. C_1AC_2 is called the crank acute angle between the two limiting positions, denoted as θ. If the input crank AB rotates counter-clockwise, the rocker will rock from its right limiting position DC_2 to its left limiting position DC_1, when the crank turns through the angle $(180° + \theta)$ from AB_2 to AB_1. Next, the rocker will rock back from DC_1 to DC_2 when the crank turns through the angle (180°-θ) from AB_1 to AB_2. If the input crank AB rotates counter-clockwise at a constant speed, the average angular velocities of the rocker DC in the two strokes of the follower are different. The ratio of the faster average angular velocity w_f to the slower one w_s is called the coefficient of



(a) (b)

(c)

FIGURE 7 Three snapshots from motion simulation in AR environment in the second mode (a) position one, (b) position two, and (c) position three

travel speed variation, denoted as K. Therefore,

$$K = \frac{w_f}{w_s} = \frac{\varphi_{\max/t_f}}{\varphi_{\max/t_s}} = \frac{t_s}{t_f} = \frac{180^{\circ} + \theta}{180^{\circ} - \theta} \tag{10}$$

where t_f and t_s are the time durations for the faster stroke and the slower stroke, respectively.

5.3.2 | Quick return characteristics analysis in AR environment

According to the definition of the Quick return characteristics, the analysis can be implemented in the AR environment following three main steps:

(1) Pressing the button of *Modeling* to build the virtual model of the four-bar linkage, as shown in Figure 10a.

(2) Rotating the crank to the left limiting position and pressing the button *left limiting position* to record this position, as shown in Figure 10b.

(3) Rotating the crank to the right limiting position and pressing the button *right limiting position* to record this position, as shown in Figure 10c.

After these steps, the values of the angular stroke of the rocker, the crank acute angle and the coefficient of travel speed variation are rendered on the AR scenes. Through the interaction with the AR scene based on the interaction tool which is the physical four-bar linkage model, users can understand deeply and visually the theoretical bases.

5.4 | Dynamic analysis module

The DA module provides dynamics analysis for students to understand the loading condition of a structure by setting up

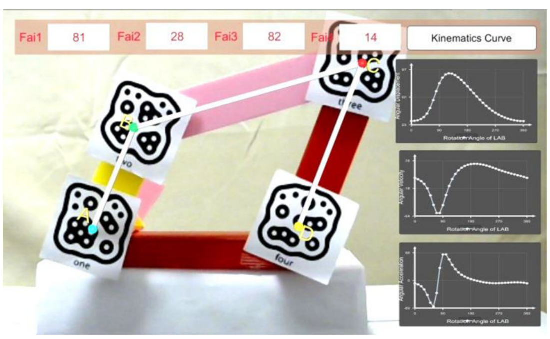


FIGURE 8 Simulation results rendering

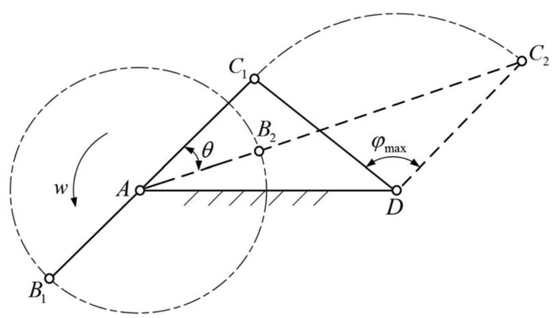
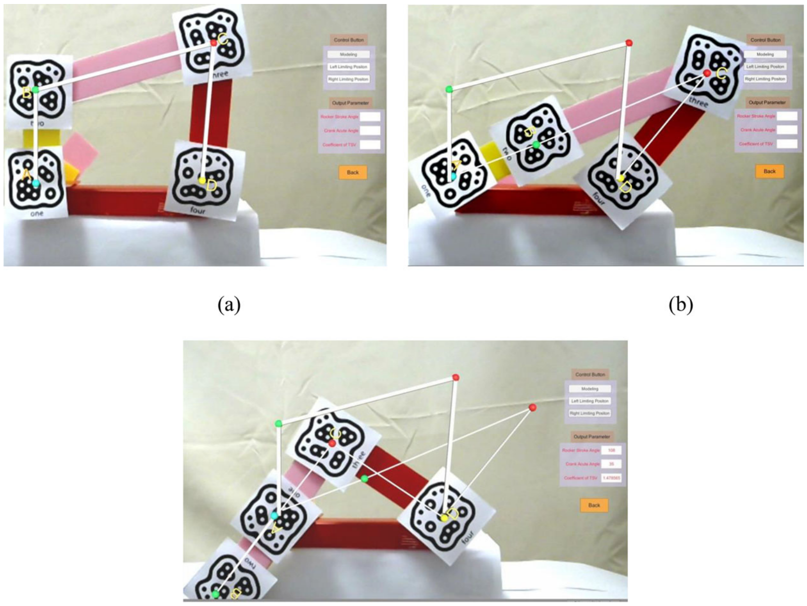


FIGURE 9 Quick return characteristic diagram



(a)

(b)

(c)

FIGURE 10 Three snapshots from kinematical characteristics analysis in AR environment (a) modeling, (b) left limiting position, and (c) right limiting position

relevant parameters. For example, as shown in Figure 11, a four-bar linkage is in equilibrium under the action of the external force F, M_r, and M_b. The magnitude and direction (θ_F) of the force F and the magnitude of the torque M_r are known. M_b and the forces acting at the joints need to be calculated to show the loading conditions of the structure. The unknown joint force components (F_{Rijx} and F_{Rijy}) are all shown acting in the positive X and Y directions. A negative value obtained in the result means that the force component is in the opposite direction. In the example shown, equilibrium equations resulting with nine scalar equations in nine unknowns are as follows.

For rocker CD,

$$-L_3F_{R23x}\sin\alpha_3 - L_3F_{R23y}\cos\alpha_3 - M_r = 0 \quad (11)$$

$$F_{R23x} + F_{R43x} = 0 \quad (12)$$

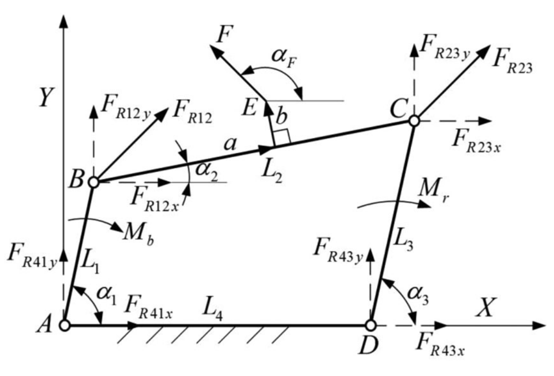


FIGURE 11 Force analysis diagram

$$F_{R23y} + F_{R43y} = 0 \quad (13)$$

For coupler BC,

$$L_2F_{R23x}\sin\alpha_2 + L_2F_{R23y}\cos\alpha_2 - aF\sin(\alpha_2 + \alpha_F)$$
$$-bF\cos(\alpha_2 + \theta_F) = 0 \quad (14)$$

$$F_{R12x} = F_{R23x} - F\cos\alpha_F \quad (15)$$

$$F_{R12y} = F_{R23y} - F\sin\alpha_F \quad (16)$$

For crank AB,

$$M_b = -L_1\left(F_{R12x}\sin\alpha_1 + F_{R12y}\cos\alpha_1\right) \quad (17)$$

$$F_{R12x} + F_{R41x} = 0 \quad (18)$$

$$F_{R12y} + F_{R41y} = 0 \quad (19)$$

From these equations above, it can be seen that the construction of the dynamic equations based on the equilibrium principle is easy, but the solution process is difficult. There are nine equations with nine unknowns; hence, a large number of calculations is needed. To help users obtain the loading condition of the structure easily, the DA module is developed. Students only need to input all the known parameters in the AR scene, these nine equations will be solved automatically and the results will be rendered in real time, as shown in Figure 12.

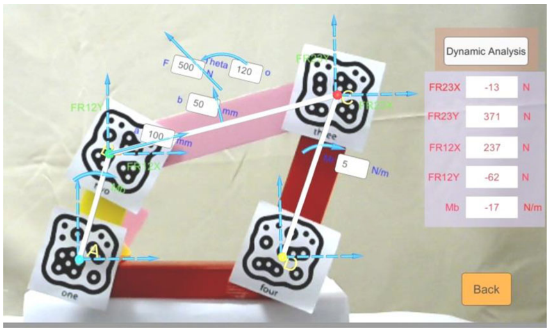


FIGURE 12 Dynamic analysis in AR environment

5.5 | Dimensional synthesis module

The DS module provides some practical exercises to help students understand visually the main ideas of the synthesis. For example, the length of the coupler *BC* is required to increase with unchanged position; it will cause a classic synthesis problem called body guidance. The user needs to find three new positions of the pivot. The solution procedures of this problem can be implemented in the AR environment using the following four main steps:

(1) Rendering a virtual pivot based on the position and height of the coupler *BC* together with the new length requirement.
(2) Rotating the crank three times to locate three new positions of the virtual pivot.
(3) Calculating the center of the circle based on the three positions.
(4) Implementing motion simulation to evaluate the new mechanism.

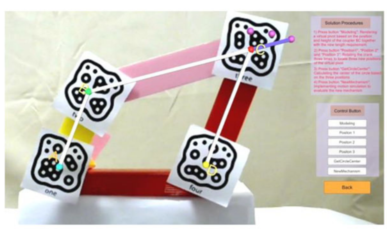
All these steps will be rendered in the scene, as shown in Figure 13. Students can solve the synthesis problem by pressing the buttons on the interface to conduct these procedures one by one.

6 | EVALUATION OF THE SYSTEM

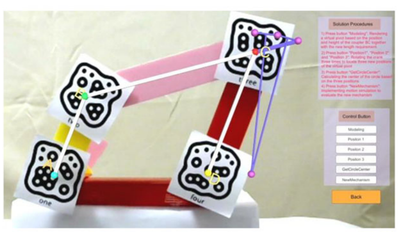
6.1 | Evaluation setup

The aim of this paper is to provide an AR mechanisms education system. By leveraging on the characteristics of the AR technology, this system is expected to enhance the education of mechanisms with a high level of interaction, easy modeling and simulation environment and practical exercises with real mechanisms. The evaluation of this system will be performed with respect to these features. As shown in Table 1, a questionnaire based on the five-point Likert Scale was designed to measure the performance of this system as an education tool. There are 12 questions. The evaluation scale ranges from 1 to 5, where 1 means "Strongly disagree" and 5 means "strongly agree." Q1 to Q9 in the survey are used to evaluate the performance of different modes and modules in the system. Q10 to Q12 are used to evaluate the comprehensive performance of the system. Although the main target users of the system are students, it can also be used by teachers to deliver lectures in class. Twenty persons composed of 16 students and four teachers from Ningbo University were selected, and they were from the department of mechanical engineering. They were given an introduction of AR and the basic operation of the ARMES system. After using the system, they were asked to complete the questionnaire.

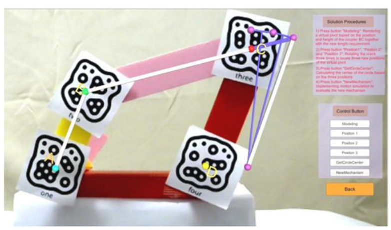
(a)



(b)



(c)



(d)

FIGURE 13 Dimensional synthesis in AR environment (a) rendering a virtual pivot, (b) locating three new positions, (c) calculation the center, and (d) simulation

TABLE 1 The survey used to evaluate the system

Question	Evaluation scale: Strongly disagree	Disagree	Neither	Agree	Strongly agree
Q1 The animation of mechanisms rendered above the book helps me understand the theory easily	1	2	3	4	5
Q2 The information provided by AR makes it easy to find the related content in a book	1	2	3	4	5
Q3 It is easy to construct the virtual model of a mechanism using markers	1	2	3	4	5
Q4 It is easy to make simulation of a mechanism using the system	1	2	3	4	5
Q5 The way to conduct kinematic characteristics analysis helps me understand theories behind deeply	1	2	3	4	5
Q6 The way to conduct kinematic characteristics analysis makes it easy to work out the solutions	1	2	3	4	5
Q7 It is easy to visualize and understand the kinematics and dynamics of a mechanism	1	2	3	4	5
Q8 It is easy to solve kinematic and dynamic problems using the system	1	2	3	4	5
Q9 Performing the practical exercise under the guidance provided by rendered information make me understand the synthesis concepts easily	1	2	3	4	5
Q10 It is a useful tool for self-study	1	2	3	4	5
Q11 The learning style provided by the system enhances my learning motivation	1	2	3	4	5
Q12 I can understand mechanisms in a better way with this kind of system	1	2	3	4	5

7 | RESULTS AND DISCUSSION

The results obtained for each question are shown in Table 2. The scores of Q1 and Q2 indicate that interaction with the rendered animation and information has helped the users in grasping the theory easily. The scores of Q3 and Q4 indicate that users generally agreed that the modeling and simulation of a mechanism in the system is easy to conduct. The scores of Q5, Q6, Q7, and Q8 indicate that the system improves the users' understanding of the behavior of the mechanisms and is helpful to the users in solving analysis problems. The score of Q9 indicates the way to solve a synthesis problem makes the learning of the synthesis theory easily. The scores of Q10, Q11, and Q12 indicate that the whole system shows positive results in enhancing learning. As a general result of these responses,

TABLE 2 Ratings given by the participants

System evaluation response rate	Strongly disagree	Disagree	Neither	Agree	Strongly agree
Q1	0	0	3	7	10
Q2	0	2	3	10	5
Q3	0	0	4	9	7
Q4	0	0	4	10	6
Q5	0	1	3	10	6
Q6	0	1	2	12	5
Q7	0	2	2	13	3
Q8	0	3	4	11	2
Q9	0	3	2	12	3
Q10	0	2	2	11	5
Q11	0	1	3	11	5
Q12	0	0	2	14	4

by leveraging on the characteristics of AR, the modules presented in this paper are helpful in improving the interaction, visualization, and practicality of the mechanism problems. These features can make the system a powerful tool for the education of mechanisms.

8 | CONCLUSION

An AR-based simulation has been proposed to enhance the learning of mechanisms. In the AR environment, the theories can be learned through interaction with the rendered animation and information, and the practical exercises are performed based on motion simulation of the virtual model of a real mechanism. To provide an easy modeling and simulation environment for users, modeling and simulation based on markers is proposed. After attaching the markers to a real mechanism, the virtual model will be superimposed automatically, and the kinematics equations will be solved with the motion of the real mechanism to conduct the simulation. In addition, based on motion simulation, practical exercises regarding characteristics analysis, dynamic analysis and synthesis can be conducted easily by moving the real mechanism to update the AR scene and following the guidance provided by rendered information.

Based on the survey results, it is observed that (1) the interaction with rendered animation and information helps users in grasping the theory easily; (2) the modeling and simulation of a real mechanism has been found to be easy; (3) the understanding of the kinematic and dynamic behavior of the mechanisms has been improved; and (4) the way to solve synthesis problem make the learning of the synthesis theory easily. These features make the system a powerful tool for the learning of mechanisms.

In future, several research issues will be explored. Students require multiple sources and forms of guidance and information during the learning process. Therefore, pertinent information has to be filtered, organized, and executed appropriately according to user cognition. From a technical perspective, this can be realized with a context-aware system equipped with multiple sensors. Context-awareness will be integrated into the system to provide more appropriate guidance for the learning of mechanisms. In addition, enhancing the practical skills by using the system to outdoor mechanisms will be explored to enrich the system. Further, experiments will be designed and conducted to evaluate the learning outcomes of this system, such as knowledge retention, understanding and application.

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