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INTRODUCTION

Many engineering subjects require modeling, analyzing, or simulating dynamic phenomena (e.g., physics, kinematics, dynamics, heat transfer, fluid flow). The standard tools for teaching these subjects, such as the blackboard and overhead projector, fall far short of being dynamic. It is well recognized that interactive computer graphics can aid tremendously in the visualization of concepts [1]. Many Computer-Aided Instruction (CAI) packages have been developed in the engineering field [2, 3]. The majority of these fall into the category of "tutorials", in which a student works through a planned lesson on the computer with various opportunities for experimentation, testing, and repetition. Some of the tutorials incorporate artificial intelligence in an effort to account for the variations in learning styles. These CAI packages have generally been considered successful in meeting some of the needs of education, e.g., self paced study, opportunities for experimentation, and increased interest [4].

The trend has been to use these packages to decrease the use of formal lectures by an instructor. However, solid evidence of the desirability of using packages such as these to replace the instructor is lacking. In fact, the authors firmly believe that a good instructor cannot be replaced by the computer, but can be assisted by the computer. However, only a few of the CAI packages are designed for actual use in the classroom as a tool for the instructor. In general, instructors are still using traditional teaching methods and tools in the classroom, with an occasional computer demonstration. The result is that the computer-aided instruction is occurring outside the classroom [5]. The exception to this is the use of courseware and authoring tools to prepare a dynamic lecture. This type of in-class use of software is severely hindered by the inordinate amount of time necessary to prepare each lecture. With the availability of high quality computer projection systems and multimedia integration systems it is practical to develop CAI packages specifically tailored to provide the flexibility needed in the classroom [6, 7].

Various computer aided packages are available and under development in the kinematics field [8, 9]. They can generally be classified as industrial, tutorial, or simulation packages. The industrial packages are primarily intended for obtaining answers to problems. In the educational setting, they are valuable for projects and practical examples, but are generally cumbersome and ineffective in the conceptual and theoretical phase of teaching. In fact, one can often use the packages with limited knowledge of the theory on which they are based. The tutorials supplement the classroom instruction [10, 11]. The simulation packages are useful both for student experimentation and for classroom demonstration [11]. Although any of these packages can be used in the classroom, none of them are specially designed for everyday use as the primary teaching tool. It must be emphasized that the existing software packages are not designed to fill the needs encountered on a daily basis in the classroom.

A CAI package is being developed to be used as a classroom tool for the instruction of undergraduate mechanical engineering students in an introductory kinematics of mechanisms course. This graphical environment allows the instructor to emulate on the projected graphics screen everything that is currently done on the blackboard for planar mechanisms. Unlike the blackboard, the software will have the intelligence to interpret the drawings in a kinematic sense so that the drawing of the linkage will behave as a linkage. Likewise, all constructions and concepts based on a linkage will be directly associated with the linkage, even as the linkage dynamically moves to its next position. The current classroom method for teaching kinematics of mechanisms relies heavily on blackboard drawings of linkages and various geometric constructions related to the linkages. Since the linkages are intended to have mobility, every drawing is an instantaneous snapshot of the linkage or the construction. Erasing and redrawing in the next position is cumbersome, time-consuming, and confusing. Frequently this step is omitted and the students have difficulty visualizing the time dependent nature of the problem. They do not always acquire an intuitive feel for the dynamic behavior of linkages.

The software environment involves three principal components: (1) The sketching method for defining the linkage, (2) the "kinematic intelligence" to interpret the sketch and animate the linkage, and (3) the ability to develop and demonstrate kinematic concepts. The major objectives, along with justifications, for all three components are outlined below to provide a comprehensive view of the entire software environment. Further details of the sketching method are given in [12]. Details of the second section are given in [13].

SKETCHING METHOD

One of the most significant requirements for a kinematically intelligent blackboard is for the sketching process to be rapid and intuitive. An instructor must be able to sketch arbitrary planar linkages as easily and quickly on the electronic blackboard as on the traditional blackboard. The software under development provides a unique sketching method which allows the schematic diagram of practically any planar linkage to be intuitively sketched on the graphic screen in a matter of seconds, typically as fast as drawing by hand on paper. The method separates the process of defining topology from the definition of dimensions [14]. This allows the sketching process to flow smoothly and intuitively, simulating the process of sketching by hand. If the linkage is treated as a series of closed loops, it is reasonable to assume the user will start either at a grounded joint or a previously defined joint, then alternate
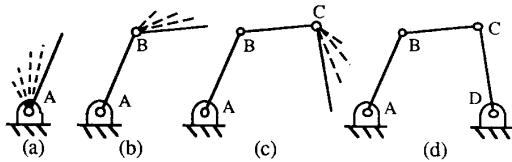
Figure 1. Construction of a Simple Fourbar

between links and joints until the loop is closed. Once this pattern has been decided upon, it is not necessary to tell the computer that we intend to draw a link between successive joints.

By way of illustration, assume that a four bar linkage as in Figure 1-d is to be sketched. The user would begin the loop by pointing to the location of joint A with the pointing device (mouse, light pen, etc.) and marking it with a defined key which specifies that the joint is a grounded revolute joint (pin joint). The grounded revolute is drawn immediately. As the user moves the cursor, a link is stretched from the grounded revolute (Fig. 1-a). This stretching continues until a key is struck marking the location and type of joint B. Joint B is drawn, locking into place the link between A and B, and a new link begins stretching from joint B (Fig. 1-b). Mark the location of joint C and the same process occurs (Fig. 1-c). When joint D is marked, a grounded revolute is specified, indicating that the loop is closed by automatically connecting the ground link. Once a loop is closed, the cursor is disconnected from the linkage, allowing it to move to a new location and start another loop. A loop may be started by creating a grounded joint, connecting to an existing joint, or adding a new joint to an existing link. Notice the similarity to pencil and paper sketching. The sketch starts at a ground point, draws joint A, draws a link to the approximate location of joint B, draws the joint, draws the next link, draws joint C, draws the final link, and closes the loop with the ground joint. On the computer, all of this takes exactly four keystrokes, one for each joint, and about the same length of time as drawing on paper.

One factor which facilitates the rapid sketching is the definition of several standard joint types which are actually common combinations of revolute (pin) and prismatic (sliding) joints. These joints are shown in Figure 2. With these joint type definitions available at the stroke of a key, practically any planar mechanism consisting of revolutes and prisms can be quickly and easily sketched.

Much of the material is best taught with wireframe drawings. However, it is often helpful to add points of interest, width, or complex shape to the drawing. The .sketch method creatively provides a combination of capabilities which is extremely flexible and efficient to use. Details of the sketching method are given in (Nisbett, 1993a) Wireframe sketching as previously illustrated in Fig. 1 is the default. If at any time during the stretching of a wireframe link the pointer button is clicked, the wireframe is bent at that location. As many bends as desired may be placed to create a wireframe with bends. If the wireframe closes back onto itself at any point, the closed section becomes a solid part of the link. In this way, a portion of a link can be wireframe while another portion is solid. As an example of the effort involved, a linkage with six links, six revolute joints, and one prismatic joint was tested (see Figure 3). This type of problem is typical of the complexity of most classroom examples. The linkage was easily sketched in less than ten seconds, requiring only seven keystrokes.
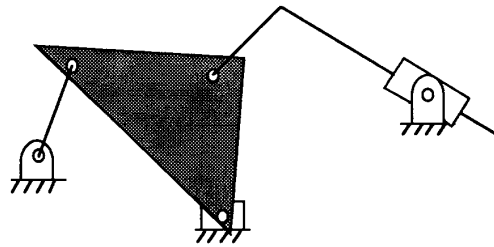

Figure 2. Common Joint Definitions

Figure 3. A typical example.

A more complex linkage, a front end loader (Fig. 4), is easily sketched in about 40 seconds. The reader is encouraged to sketch this linkage by hand for a comparison.

It is difficult to convey the feel of this dynamic sketching method with words and still pictures, but we hope that this description at least conveys a glimpse of the reality. This sketch capability will provide a definite boost to the feasibility of using the computer in place of the blackboard.

INTERPRETATION AND ANIMATION

Once the topological description is complete, the software has enough information to recognize the type and general shape of the linkage. An appropriate data structure is used to automatically store the information as it is sketched. The linkage is dimensioned by default as sketched, which is usually sufficient in the classroom. All dimensions are automatically evaluated to distinguish between constants and variables. This means that the user can go directly from sketching a linkage, such as previously shown in Fig. 3, to animating with no intermediate steps. Various options for animating are available, including single stepping and full range of motion. The most convenient and effective method simply allows the pointer to touch and highlight any link to be used as the input, then the pointer button is pressed and held to grab onto the link and start pulling it around. The linkage animates in response to the specified position of the input link. Thus the user can sketch a linkage in a matter of seconds, then immediately "grab" an input link with the cursor and begin moving it around to animate the linkage. Details of the algorithms and data storage are given in [13].

KINEMATIC CONCEPTS

Although simulation of motion is a tremendously valuable component of this tool, the more far-reaching aspect of the proposed environment is the ability to develop and demonstrate every kinematic principle for any planar linkage at any time. As an example, consider a simple four-bar linkage as shown in Fig. 5-a. Most students can readily understand the idea that point A attached to body 3 will trace a specific path with respect to the ground link as the linkage is animated. However, it is a much more difficult task to communicate to students the concept of the path traced by point B attached to link 2 with respect to link 4, which is
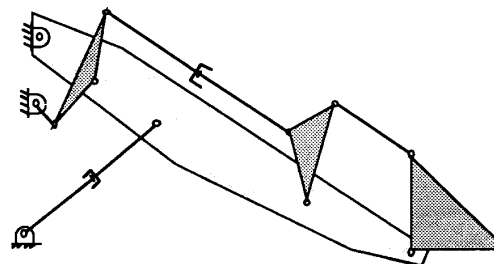

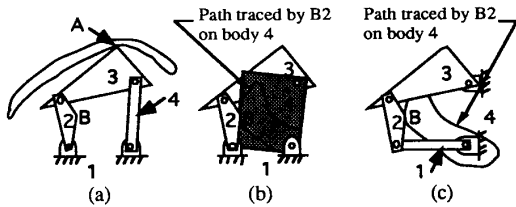Figure 4. A schematic of a front end loader.

Figure 5. Demonstration of path traced by a point.
    (a) Path of A$_3$ with respect to the ground.
    (b) Path of B$_2$ on link 4.
    (c) Inversion with path of B$_2$ on grounded link 4.

itself moving. This concept is difficult to demonstrate on a static blackboard, but will be effectively shown on the computer using the proposed environment. Link 4 can be "stretched" out so that it is visualized as a moving plane rather than a line or thin rod. Now as the linkage is animated, the students can watch point B as it traces a path on the plane of link 4, even though both links are moving. (See Fig. 5-b for a limited static picture of the dynamic concept.) The concept can be further clarified by performing a kinematic inversion in which link 4 is temporarily considered as the grounded link. Now point B can be demonstrated to trace exactly the same path as before, though much more intuitively anticipated with a stationary link 4 (See Fig. 5-c).

Although the concept in this example is used continuously throughout the course, it is typically only demonstrated once, if at all. This kinematic software environment would allow the principle to be readily used to prove other concepts throughout the course. This is a departure from the typical modular approach to teaching kinematics. Usually, topics are taught in sequence with only cursory references to previous topics. The kinematically intelligent blackboard will provide an environment in which all topics and principles can be integrated. This point was illustrated by the previous example, in which the concept of relative motion through kinematic inversions was related to the concept of paths traced by points with respect to moving bodies.

This environment should be contrasted with the traditional analysis, synthesis, and simulation software packages. Although the environment will obtain answers, its primary intent is to demonstrate the principles involved in obtaining the answers. The environment is also a departure from the standard concept of using the computer in the classroom to perform occasional demonstrations. Instead, the computer is to be used on a daily basis as a tool to develop and explain the principles involved. In addition, each principle should be readily available in the standard environment to reinforce a concept for any example or homework problem that the students may have difficulty understanding.

The following kinematic concepts are to be included in the initial development of the environment.

1. *Mobility.*
2. *Range of motion.*
3. *Kinematic inversion.*
4. *Loop closure.*
5. *Multiple forms of assembly.*
6. *Path traced by any point of any link on any other link.*
7. *Velocity and acceleration polygons.*
8. *Instant centers of velocities.*

This list is representative of only some of the desirable capabilities which are achievable, but these would handle many of the topics included in an introductory level course.Extension of the capabilities to include cams, gears,

and force analysis should eventually be added for completeness in the introductory level. The software environment could also be extended to integrate more advanced topics such as kinematic synthesis and curvature theory.

It should be emphasized again that the capabilities listed should be available in the environment, individually or in combination, to be used with any homework problem or example problem which may come up for discussion. The construction processes will generally have three levels of operation. A fully manual mode allows the instructor to completely dictate the construction process, including the possibility of making mistakes. This is most useful the first time a concept is introduced. A semi-automatic mode allows the instructor to step through the standard construction process, but the environment uses the programmed intelligence to predict the next step. This allows the instructor to talk through the entire construction process. The instructor controls *when* the next step occurs, but is not required to carry out all the details manually. This is most useful when a concept is being repeated on subsequent example problems. A fully automatic mode allows the instructor to obtain in an instant the entire construction or the result of the construction. This is most useful when the information is needed, but the process of obtaining the information is already well established and need not be repeated.

EXPECTED IMPACT

Educational Improvements

The kinematically intelligent blackboard is a desirable and feasible tool with which to enhance the efficiency and quality of education of engineers. The advantages of the software environment can be realized in five areas:

(1) Concepts can be *taught* more easily.
(2) Concepts can be *comprehended* more easily.
(3) Concepts can be understood *more deeply.*
(4) More examples can be considered.
(5) More interest from the students will result from understanding how the material is used for analyzing real machines.

The first two areas deal primarily with efficiency in the education process. A well structured environment should avoid the confusion resulting from demonstrating dynamic principles on a static blackboard. Geometric constructions can be performed manually, semi-automatically, or automatically. Parts of the construction can be turned off when they are not needed and turned on when they are helpful. In short, less time can be spent verbally explaining and manually constructing, and more time can be spent in demonstrating. A side effect which must be carefully avoided is a pace of presentation which does not match the ability of the students to take notes and to absorb the information. The expectation is that the efficiency will come not from a faster pace, but from eliminating wasted effort in trying to make a point without appropriate tools to demonstrate the point. It should also become less necessary to repeat and re-explain the material that was not effectively taught the first time. A comparison could be made to the added benefits of demonstrating real hardware rather than drawing pictures of it. Even though the students have less time to take notes, they understand the hardware much better after having seen it.

The third area is probably the most significant in that it addresses the need for developing the intuition of engineers. A large part of understanding the study of mechanisms is dependent upon the ability to visualize motion. It is important to be able to relate a sketch of a machine in the form of a schematic diagram to the real machine. It is also

necessary to interpret the type of motion each link exhibits and the range of motion which can result from the arrangement of the links. In comparison to previous students, the investigators have observed that students today have not had as much exposure to real machinery and consequently have less in their background to help them understand and interpret kinematic diagrams and motion characteristics. With the decrease in available candidates for engineering students, the percentage of students from non-mechanical backgrounds is likely to increase. This teaching environment should provide an opportunity to continually demonstrate concepts during the daily teaching sessions. Abstract concepts can also be presented visually and interrelated to concepts previously learned.

The fourth and fifth areas are greatly enhanced by integrating the kinematically intelligent blackboard with the multimedia enhancements. A common complaint from students is the lack of realistic applications of theory. This software environment is expected to provide a significant connection between real hardware and kinematic principles.

Impact on Specific Classes of Students

Each of the areas of improvement just mentioned seem to be particularly critical for certain categories of students. In addition to the general decrease in mechanical intuition among all students, women and disabled students would be expected to be further disadvantaged due to the fact that they have generally had even less "hands on" experiences with machinery. Researchers are confirming that the ability to visualize is an important skill in learning science [15]. Recently, in the National Geography Bee, out of 5000 state winners, 1000 were young women. Only two were among the 57 finalists [16]. Researchers believe that a lack of graphic literacy may be a factor in the performance of the young women.

Another factor relates to the different psychological types among engineering students and the manner in which they learn. An ASEE study using the Myers-Briggs type indicator has shown that engineering students are about evenly divided between "sensor" and "intuitor" types [17]. Each of these types learns best in very different ways. The sensor type is characterized by a need to touch, feel, see, or experience things in a methodical way in order to effectively learn. This type of learner would typically have more difficulty in immediately making the connection between an abstract concept and the practical application, or between a schematic diagram and the dynamics of the real hardware. Interestingly, estimates show that 75% of engineering professors are intuitor while 50% of all students are sensor types. It is also estimated that 75% of minority students are sensor. The proposed software should be of assistance to all of the students, but is expected to be especially useful for those with the sensor learning type due to the addition of the extra dimensions provided by the environment. They will be able to "feel" the links move as they provide the motion to the input link, as well as see the effect the motion has on various parameters and constructions.

Assessment and Evaluation

The extra cost and effort required to make this teaching tool available must be justified in recognizable improvements in such things as efficiency, understanding, and interest levels. These qualities are difficult to measure quantitatively. However, a significant effort is to be made as part of this project to evaluate the worthiness of this type of classroom tool.

It is anticipated that this software will not necessarily dramatically improve the performance of students on a typical exam. This is because the exam usually consists largely of measurable evaluations, such as problem solving. Most students are eventually able to learn to repeat a procedure, even with poor instruction. Improvements are expected in such things as interest, depth of understanding, intuition, estimating ability, and ability to extend concepts. To evaluate these qualities, a qualitative and conceptual exam will be administered to students in all sections of the course, of which only some of the sections used the software. This type of exam could contain questions that required little or no calculations, but would require a mastery of concepts to perform well. For example, a slide of a particular linkage could be displayed for a specified length of time, during which the students are asked to answer certain questions such as "Estimate the mechanical advantage," "Estimate the angular velocity of the output link," "Determine the mobility," "Can the input link make a complete revolution?" These types of questions can be answered very quickly by someone experienced with linkages, but can only be answered using procedural calculation by inexperienced people. The goal is that with exposure to the kinematic blackboard, the students will gain a significant amount of experience and comprehension to be able to answer these types of questions.

Recruitment and Retention

This software environment is expected to play an important role in increasing student interest in mechanical engineering and could be used for recruitment purposes. The introductory kinematics course is typically one of the first engineering courses taken. The course deals with moving parts, realistic hardware, and interesting synthesis tasks. The kinematic blackboard takes advantage of the visual nature of kinematics. In addition to being used in the introductory kinematics class, the kinematic blackboard would be an ideal tool for use in a short course or demonstration for high school students or entering freshmen.

Prototype of Computer Aided Instruction

The concept of CAI packages tailored specifically for classroom use is not limited to the application proposed here. There is a tremendous potential for revolutionizing the classroom environment for any educational topic, particularly when dynamic phenomena are present. It is expected that the classrooms of the future will replace the traditional blackboard with large computer screens which also serve as positional input devices, similar to a touch sensitive screen. This would allow the instructor to write and draw directly on the screen, with efficient erasing capability. Images can be saved, recalled, and printed for students. Hardware and software is currently available to allow spoken words to be recognized and treated as commands. This could be particularly useful in the sketch process. The instructor could simply speak the type of joint desired while sketching the linkage, rather than looking down at the keyboard to find the appropriate key. Sound input would free the instructor from sitting at the keyboard. The proposed software environment would take full advantage of the hardware by customizing the "intelligence" of the blackboard for one course.

The software environment is envisioned to take advantage of multimedia audio and visual input to allow the kinematic blackboard to overlay images of actual hardware, from sources such as a videotape or CD drive. It is possible to videotape an actual machine in motion and demonstrate its gross motion characteristics during playback on a computer screen. With the use of multimedia integration hardware and software, the videotaped image can be frozen and the image digitized. Then, the sketching capability of the kinematically intelligent blackboard will be overlaid to define the kinematic representation of the machine on the captured image of the playback. This feature should enhance the interest and learning of the students by bridging the gap between real hardware and the kinematic models. It will also relieve the instructor of the time consuming task of entering realistic

dimensions for the simulations by sketching the kinematic diagram directly on the image of the actual hardware. Many more examples, with much improved realism, can be incorporated in a lecture with the capabilities of the multimedia presentation facilities.

The software environment should be able to incorporate the digitized image as a background. Furthermore, it is envisioned that eventually the environment will be activated by voice commands to free the instructor from standing at the computer. Though these features may not be fully implemented in this proposed project, the overall design takes them into consideration. The kinematic aspects of the environment are to be fully functional with only a standard desktop computer configuration. The quality of the projection system and availability of multimedia hardware will add to the efficiency and effectiveness of the environment, but will not be the limiting factor on the use of the system.

Efficiency
To be used in the classroom, the software must be designed to be extremely intuitive and convenient. It is intended to be used as an aid in teaching, thus the details of making it work should not be a hindrance to either the instructor or the students. Since the software is to act as an intelligent blackboard environment, as opposed to a prepared lecture, it should not require any more preparation time outside of class than usual. Each instructor should be able to use the environment to enhance personal teaching styles and methods.

Since the environment is to operate on a standard computer, it can also be used in an office or computer lab setting. It will be an effective tool with which the instructor can give additional help or explain concepts more deeply on an individual basis during an office visit. The students can also experiment, individually or in groups, with the tool in a computer lab. In contrast to a tutorial environment, however, the students will be working in a study and experimental environment. This should work well since the students will see the software in operation on a daily basis in the classroom and can duplicate procedures and examples previously demonstrated by the instructor.

CONCLUSIONS
The kinematically intelligent software environment is designed for daily classroom use. The unique sketching method provides an efficient method of defining planar linkages, allowing a combination of wireframe and shape representations. The software provides an integrated environment for relating various kinematic concepts. While most kinematic software can provide simulation of motion, this environment is unique in its focus on presenting the actual kinematic concepts in a dynamic manner. This type of teaching tool is expected to improve the interest and depth of understanding and intuition of engineering students.

ACKNOWLEDGMENTS

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