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TOOLS TO ASSIST TEACHING AND LEARING OF MECHANISMS, ROBOTICS, AND BIOMECHANICS

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ABSTRACT

This paper details some innovations developed at Ohio University for augmenting the teaching and learning of mechanism kinematics and dynamics, robot kinematics, dynamics, and control, and the musculoskeletal biomechanics of human motion. Common to all three courses are NotesBooks, significant MATLAB use in class, homework, and projects, term projects simulated from real-world applications, and Internet resources developed and hosted by the author at Ohio University.

INTRODUCTION

This paper describes modern teaching tools developed over the past 15 years by the author at Ohio University for motion and dynamics-related courses. The old, well-developed topic of kinematics and dynamics analysis of mechanisms is taught largely using a modern analytical algebraic matrix/vector approach, augmented with a real-world approach and various computer tools. The newer but still well-developed topic of kinematics, dynamics, and control of robots is also taught using a matrix/vector approach, augmented with a real-world laboratory and various computer tools. The much-newer discipline of human motion biomechanics of is included here due to the relationship to the previous two topics.

This paper is organized as follows. First, the three courses are briefly described. Next the specific modern tools are described, many common to two or three courses. Finally the Internet resources are described including mechanism and robot CAD animations, an atlas of structures, mechanisms, and robots, NotesBook supplements, and a general MATLAB primer, all developed by the author and freely available.

The pertinent website is oak.cats.ohiou.edu/~williar4; choose Teaching and then Ohio University Courses.

THE COURSES

The specific Ohio University engineering courses featured here are: 1. ME 301 Kinematics and Dynamics of Machinery, a traditional required junior mechanical engineering course, taught in a modern manner and featuring planar 1-dof mechanisms; 2. EE/ME 429/529 Robotic Manipulators, a technical elective offered to senior and graduate students in electrical and mechanical engineering, featuring spatial multi-dof robots; and 3. ME 467 / BME 567 Biomechanics of Human Motion, a technical elective for any engineering senior and a core course for the new Biomedical Engineering MS program at Ohio University, featuring musculoskeletal anatomy and physiology and modeling of human motion.

ME 301 Kinematics and Dynamics of Machinery

This course is required for all mechanical engineering students prior to the capstone senior design year and it has two mastery, two competence, and one awareness ABET outcomes for our program. The course focuses on the kinematics and dynamics analysis of planar 1-dof linkages, cams, and gear trains, such as the Ross-yoke Stirling engine mechanism shown in Figure 1. The course learning outcomes may be found in the on-line syllabus. The course description is:

Analytical and graphical solutions of motion problems involving mechanical elements: linkages, gears, cams, and mechanical trains.

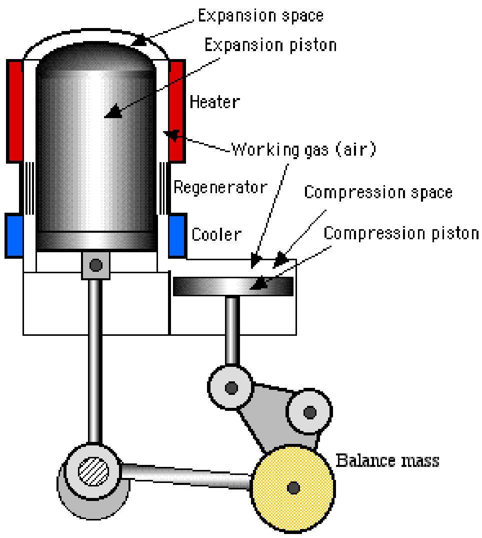

Figure 1. Ross-Yoke Stirling Engine Mechanism
www.ent.ohiou.edu/~urieli/stirling/engines/Ross_yoke.gif

EE/ME 429/529 Robotic Manipulators

This technical elective course was designed by the author partly based on his 5 years' experience as space roboticist at NASA Langley Research Center. The course focuses on the kinematics, dynamics, and control simulation of spatial multi-dof robots, such as the Adept 550 SCARA robot (Figure 2). This robot is the focus of MATLAB simulations and the weekly laboratory experiment. The course objectives may be found in the on-line syllabus. The course description is:

Classification and applications for manipulator systems. Manipulator motion description, forward kinematics transformations, and solution of inverse kinematics equations. Velocity kinematics and manipulator dynamics equations. Trajectory generation and control schemes including sensory feedback. Laboratory exercises to augment lecture material.

Figure 2. Adept 550 SCARA Robot

ME 467 / BME 567 Biomechanics of Human Motion

This new (2008) technical elective course was designed by the author based on his expertise with the kinematics, dynamics, and control of mechanical systems and partly based on his 10 years' experience with the Virtual Haptic Back team at Ohio University. The course focuses on human musculoskeletal anatomy and physiology, plus engineering mechanics applied to human motion simulations, such as for the biological system shown in Figure 3. The schedule of topics may be found in the on-line syllabus. The course description is:

Overview of human skeletal and muscular anatomy and physiology. Application of engineering mechanics to the human musculoskeletal system. Kinematics, statics, and dynamics of human motions. Human motion metrology.

Figure 3. From Bodies: The Exhibition

THE TOOLS

This section discusses some of the modern innovations developed at Ohio University to augment the teaching and learning in mechanisms, robotics, and biomechanics. Many of these tools and techniques are used in more than one course, including other courses not discussed herein.

NotesBooks®

It has been said that once one has taught a course for a decade or so, they should have a textbook as a result. This has happened to me in all the courses I teach regularly – I developed sets of notes, freely-posted on the Internet, to augment the chosen textbook in each class. Further, the increase of cost of textbooks in just one generation is out of control (I am guilty by participation, being a published textbook author[1]). Students objected to paying $200 for a new textbook that was not used nearly as much as the free supplementary notes. So in all of my courses, the unplanned evolution has been to drop the required textbook and to

[1] R.L. Williams II and D.A. Lawrence, 2007, Linear State-Space Control Systems, Wiley.

exclusively use what I call the NotesBook®, my supplementary notes that have grown to stand alone. This self-published document of about 200 pages per class has some spaces where the student must fill in equations, derivations, figures, and some examples in class. However, many figures, examples, text, and intermediate/final equations results are given in detail, in a textbook-like format. This is my only product that is not freely-available, but the Ohio University students purchase a copy for the cost of copying. Color is used strongly throughout, but is expensive to copy; therefore, the students get black & white NotesBooks® and I e-mail the class a PDF with the color pages. The table of contents of the ME 301 NotesBook® is given in the Appendix. All NotesBooks® for all courses are continually evolving.

Software

This subsection discussed the analysis, modeling, and simulation software used in all of my courses for applying the material for deeper learning and significance.

MATLAB

Our basic engineering analysis and simulation software is MATLAB. Students encounter this software in calculus and some basic engineering courses, but their first intensive exposure and challenging weekly programming occurs in my courses. MATLAB is straight-forward to use and program and includes decent, but not great, graphics, and very good plotting capabilities. It is particularly useful for performing the full range-of-motion simulation for the kinematics and inverse dynamics for a model of a given real-world mechanism. The snapshot kinematics and dynamics matrix/vector algebraic solutions are developed in class and then MATLAB is used in a loop to turn on these solutions for all possible motion. This becomes a much stronger design tool than spot-checking for the worst case forces and torques arising in motion. All students must learn to draw at least stick-figure mechanisms to the screen and animate the resulting motion, a powerful visualization and validation tool. Figure 4 shows a screen capture for a four-bar mechanism animation and Figure 5 shows a screen capture for a slider-crank mechanism animation. 3D robot stick figures can also be animated in MATLAB.

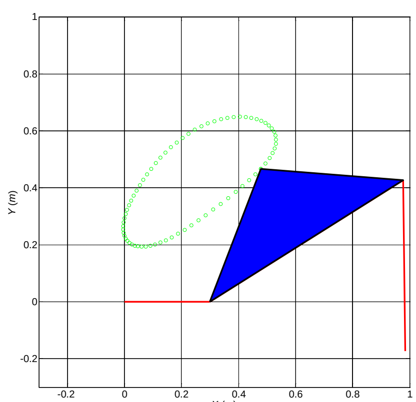

Figure 4. Four-Bar Mechanism MATLAB Animation

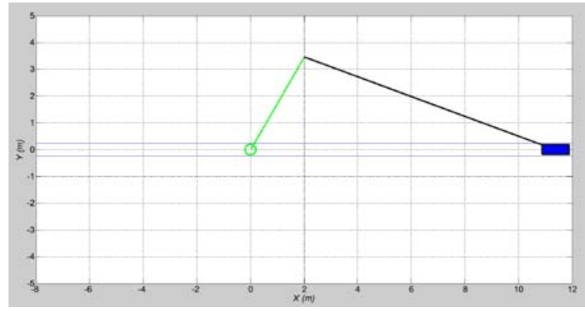

Figure 5. Slider-Crank MATLAB Animation

CAD

CAD software is applied by the students to create mechanism and robot models with much better realism than MATLAB. We use SolidEdge at Ohio University though many students prefer AutoCAD or other program learned via co-ops. Animations can be performed for simple mechanisms but in our experience these are more problematic for spatial, higher-dof, and especially parallel robot systems. Figure 6 shows a moveable CAD model for a can-crusher mechanism.

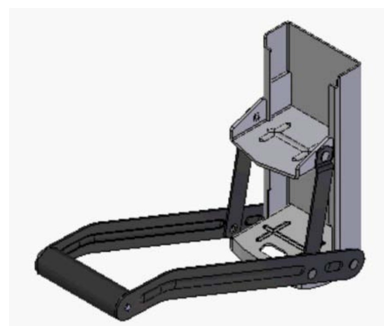

Figure 6. Can-Crusher Mechanism CAD Model

Working Model

2D and 3D Working Model software is optional in the mechanisms and robotics courses. It is very handy for quickly modeling and animating mechanisms and very useful for performing forward dynamics solutions, requiring the solution of coupled nonlinear EOMs. However, my philosophy is that students should do their own programming which is not necessary with Working Model.

OpenSim

OpenSim (simtk.org/home/opensim) is open-source software that allows users to develop human musculoskeletal models and dynamic simulations of human movement. This is an open platform developed at Stanford for the biomechanics community to share biomechanical models. Figure 7 shows a screen shot of a 3D OpenSim human walking simulation.

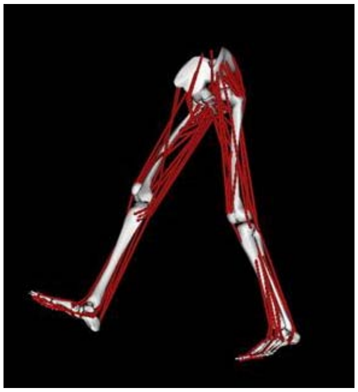

Figure 7. OpenSim Human Walking Model

Models

Low-tech tools such as physical models are also used to augment the mechanisms and robotics courses. Models of real-world mechanisms and robots are useful for in-class demonstrations and in-office discussions. Models include old commercial mechanisms specifically for teaching, a unique mechanism kit built in my woodshop (Figure 8), and LEGO mechanism models (e.g. Figure 9) are all used. In the ME 301 Term Project all student teams must build a hardware model (Figure 10) of their real-world mechanism for motion demonstrations during their presentation. The KMODDL project at Cornell University (kmoddl.library.cornell.edu) gives access to various historical mechanism models via the Internet.

Figure 8. Wood Mechanism Model Kit

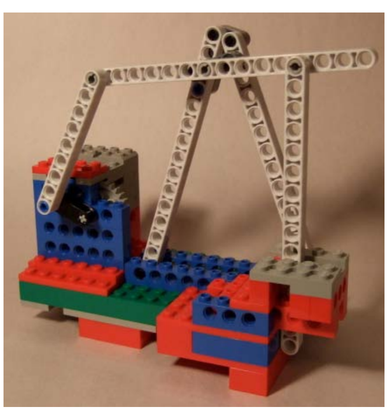

Figure 9. LEGO Oil Pump Mechanism Model

Real-World Term Projects

A feature of all my courses is a required term-long real-world project. Working in teams of two, students choose their own system from the real world to analyze in MATLAB simulation throughout the term, applying the concepts of the class. An explicit goal is for students to teach the class aspects from the real world that may not otherwise be covered in class. Figure 10 shows the ME 301 class from Fall 2009 with their term-project mechanism hardware models.

Figure 10. ME 301 Students with Hardware Models

Active Learning

The majority of contact hours with students in my classes are spent in the 15th century approach of lecture. On occasion in each course some active learning activities are used to break up the lecture pace. Significantly, all homework, laboratory, and project assignments are made with active learning in mind, outside of the classroom. In EE/ME 429/529 and ME 467/BME 567, all students must read a journal article of interest in the appropriate field and present it to the class.

Technical Writing and Presentations

In every required, core, and elective undergraduate and graduate class I teach, students must do significant technical writing and presentations. Every homework, lab report, and project report has a one-page memo written by the student to summarize the assignment and results. In addition, final technical presentations to the class are required for the real-world term projects and journal articles.

THE INTERNET RESOURCES

This section presents the specific Internet resources developed by the author at Ohio University to augment the teaching and learning of mechanisms, robotics, and biomechanics. The website is oak.cats.ohiou.edu/~williar4; choose Teaching and then Ohio University Courses. All items discussed are freely-available and external use is encouraged.

NotesBooks® Supplements

The NotesBook® concept was discussed in the previous section. Over the years I have collected and developed numerous supplementary materials that are interesting and useful but perhaps not necessarily used in the daily work in each course. This is so substantial that the supplementary material tended to double the size of the NotesBook®. Since the driving force is to give the students quality but also save them money, it was decided not to charge students for copies they may not use. Thus, the supplementary material was removed from each NotesBook®. These are freely-available on each course website and serve as a good example of what the NotesBooks® are like. In all cases, the NotesBook® supplement follows the companion NotesBook® table of contents, so the supplements appear to be incomplete when scanning their table of contents.

Introduction to Robotics

The available Introduction to Robotics is a special EE/ME 429/529 NotesBook® supplement deemed to be of sufficient interest to warrant its own link to an Internet-based PDF file (oak.cats.ohiou.edu/~williar4/PDF/IntroRob.pdf).

MATLAB Primer

As mentioned earlier, Ohio University engineering students' first intensive use of MATLAB software is in my courses, including the three courses covered in this paper. Many students struggle to learn the programming and use of MATLAB and have requested help to get up to speed. I spend only one class hour per entire term in helping students get started with MATLAB. They have said this is not enough so I started adding MATLAB sections to the NotesBooks®. Eventually I wrote a comprehensive MATLAB Primer (oak.cats.ohiou.edu/~williar4/PDF/MATLABPrimer.pdf) for the students and for free public use.

Mechanism and Robot Animations

The best student mechanism and robot CAD animations (oak.cats.ohiou.edu/~williar4/html/Animations.html) are freely-available on the Internet. The goal is to make a collection of various real-world mechanisms and robots with compelling graphics and animations. These animations were generated with SolidEdge or AutoCAD software and the student author names are given in the website. For example, Figure 11 shows a screen shot of a geared nine-bar Stirling engine mechanism animation made in SolidEdge and Figure 12 shows a screen shot of the spatial 4-dof Adept 550 SCARA robot (see Figure 2) whose animation was made in AutoDesk Inventor.

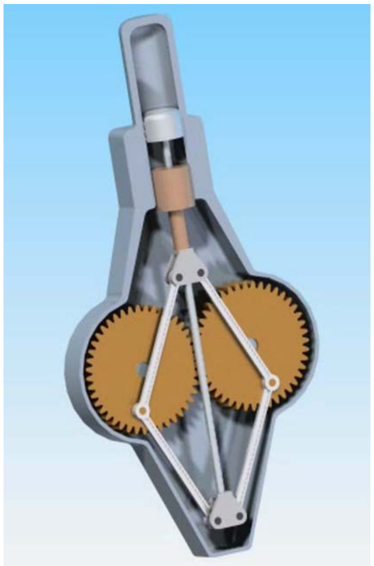

Figure 11. Geared 9-bar Stirling Engine Animation

Figure 12. Adept SCARA Robot CAD Animation

Atlas of Structures, Mechanisms, and Robots

An atlas of structures, mechanisms, and robots is posted here: oak.cats.ohiou.edu/~williar4/PDF/MechanismAtlas.pdf. This is a special ME 301 NotesBook® supplement with its own link to an Internet-based PDF file. These were drawn in AutoCAD by the author with the intent to show classification of mechanisms and many real-world mechanism examples. These show various useful mechanism types, inversions of the slider-crank mechanism, straight-line mechanisms, quick return mechanisms, compound mechanisms, six-bar mechanism types, and practical, real-world examples for 4-bar, slider-crank, 5-bar, 6-bar, 7-bar, and 8-bar mechanisms. Only 2 structures are included (statically determinate and statically indeterminate), followed by 67 mechanisms, and then 10 example robots. As examples from this atlas of mechanisms, Figure 13 shows a 7-bar car window mechanism and Figure 14 shows an 8-bar scissor lift mechanism.

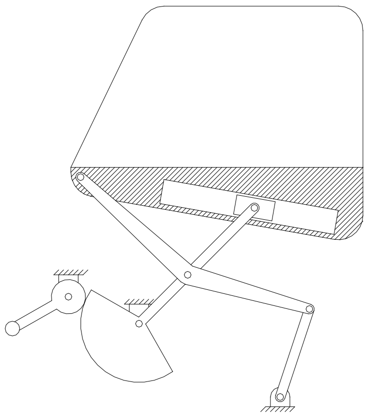

Figure 13. 7-Bar Car Window Mechanism

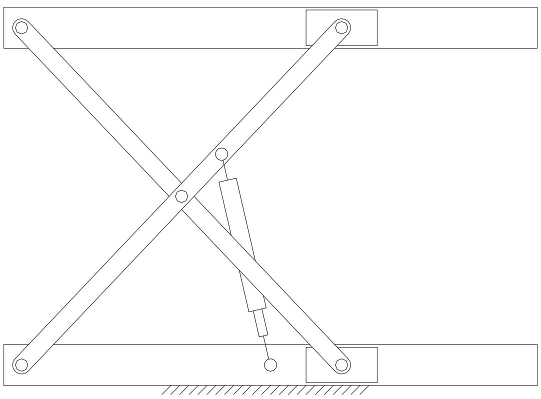

Figure 14. 8-Bar Scissor Lift Mechanism

Course Syllabi and Assignments

Though this is not an innovation but rather common these days, the syllabus, course schedule and policy, term project assignments, laboratory experiments, and journal article assignments are posted on the Internet for each course.

CONCLUSION

This paper has presented some modern teaching innovations developed at Ohio University by the author to support engineering education in the kinematics, dynamics, and control of mechanisms, robots, and human-motion biomechanics. Common to all three courses are NotesBooks, significant MATLAB use in class, homework, and projects, term projects simulated from real-world applications, and Internet resources developed by the author.

Again, the website is oak.cats.ohiou.edu/~williar4; choose Teaching and then Ohio University Courses. The author invites free use of all materials, and welcomes feedback, suggestions, and collaboration (williar4@ohio.edu).

ACKNOWLEDGMENTS

The author thanks generations of mechanical engineering students (almost 1000) over the past 15 years at Ohio University for testing the developments disclosed herein, and for feedback to improve all products. The author also thanks the specific student teams who contributed CAD animations; they are too numerous to list, but all their names appear on the website with their animations.

REFERENCES

The author has been inspired by hundreds of sources over the years and a complete listing is impossible. Given below are some seminal textbook influences in the areas of mechanisms, robotics, and biomechanics.

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Appendix: Dr. Bob ME 301 NotesBook® Table of Contents