Proceedings of DETC'04
ASME 2004 Design Engineering Technical Conferences and
Computers and Information in Engineering Conference
September 28-October 2, 2004, Salt Lake City, Utah, USA

DETC2004-57606

A FRAMEWORK AND DESIGN SYNTHESIS TOOL USED TO GENERATE, EVALUATE AND OPTIMIZE COMPLIANT MECHANISM CONCEPTS FOR RESEARCH AND EDUCATION ACTIVITES

Martin L. Culpepper
Massachusetts Institute of Technology
MIT Department of Mechanical Engineering
77 Massachusetts Avenue,
Cambridge, Massachusetts 02139
USA, 617 452 2395, culpepper@mit.edu

Soohyung Kim
Massachusetts Institute of Technology
Department of Mechanical Engineering
77 Massachusetts Avenue,
Cambridge, Massachusetts 02139
USA, 617 452 2395, sookim@mit.edu

ABSTRACT

In 2002, a Microsoft-MIT iCampus effort was initiated to generate methods and tools which accelerate the process by which students and researchers acquire perspective and skill in compliant mechanism design:

(1) Experience and skill: A synthesis tool, CoMeT, was developed as a means for researchers and students to gain experience and skill in working with old (education) and new (research) compliant mechanisms. The simulator is based on compliance theory and screw theory.

(2) Perspective: A framework, the 5 Fs, was developed to help designers form a holistic perspective on compliant mechanisms. A "big picture" view helps them systematically identify and link the important elements of a compliant mechanism problem. This opens to door for them to properly conceptualize, model and fabricate these mechanisms.

In this paper we discuss the work of early compliant mechanism/instrument designers to gain insight into how they thought about, designed and taught others about compliant mechanisms. We explain how their work has influenced the development of our framework and simulator. We then show results obtained by using the framework and simulator at MIT in:

(1) Compliant mechanism research: Generation of a compliant mechanism for an R&D 100 award winning, six-axis Nanomanipulator.

(2) Compliant mechanism education: Use within student projects to design two devices: A compliant *x-y* Nanomanipulator with 30x30 μm range and a MEMS accelerometer. Both devices are designed, fabricated and tested in a semester-long class.

The paper closes with an appendix which highlights the main steps of a CoMeT study on the screw axis characteristics of a four bar compliant mechanism. The CoMeT simulator and a CoMeT User's Guide have been made publicly available for academic use at psdam.mit.edu.

INTRODUCTION

An understanding of solid mechanics, mechanism kinematics and simulation tools is necessary, but not sufficient to be a good compliant mechanism designer. The capability of a compliant mechanism designer is primarily defined by their skill and their perspective on what is important to the design, manufacture and use of a compliant mechanism. A designer who possesses an incorrect perspective is likely to misdiagnose the bounds of the design space and therefore be unable to say that they've formulated an optimum or acceptable solution. Given the proper perspective, a designer may fully exploit the design space and produce practical and novel mechanism design concepts. Acquiring perspective and skill in compliant mechanism design is not easy. Perspective requires the ability to identify and link the important facets of a problem. Skill requires experience with the application of domain knowledge.

It is important to have a historical perspective on compliant mechanisms as a field of study so that we may understand how early mechanism designers thought about (e.g. perceived) and developed skill in compliant mechanism design. We will later show how this influences our approach to developing skill and a perspective on compliant mechanisms.

Early engineering science work in compliant mechanisms/instruments design can be found in the design activities of James Clerk Maxwell in the late 1800s. Maxwell required highly repeatable instruments, mechanisms and fixtures to support his research [1]. Toward this end, he developed a theory of mechanism/fixture design based upon constraints and compliance. Although he did not call these devices compliant mechanisms, it is clear that Maxwell accurately viewed them as devices which were enabled by elastic compliance. One may infer from his early works on constraint that he understood (at least intuitively) an important principle of compliant mechanism design, the principle of screw theory. Formal work on screw theory would not appear until 1900 when R.S. Ball first proposed a theory of modeling mechanism motions in terms of an instant screw axis [2]. In planar kinematics, this screw axis is known as an instant center (the screw axis viewed on end). This work, in combination with Maxwell's work has been used by precision engineers and physicists for over a century to design large and small-motion compliant instruments/mechanisms. From our study on this topic, we have made the following observations which set the stage for our framework and simulation tools:

(1) Early compliant mechanisms designers would design and fabricate their own devices. As such, these designers gained skill and a "big picture view", e.g. a holistic perspective of compliant mechanisms via hands-on experience in design, manufacture and application.

(2) Early mechanism designers considered how constraint, compliance and their relationships to a mechanism's motion characteristics (screw theory) are important to understanding ***how*** and ***why*** mechanism concepts might move.

These ideas formed the basis by which new compliant mechanisms were conceived, designed, fabricated and used in instruments and precision mechanisms over the last century. Until recently, this information was largely passed on through design guidelines and mechanism concepts in "story teller fashion." This is an inefficient means of advancing the state of the art (research) and educating new compliant mechanisms researchers. Our efforts have been focused on bringing this knowledge to the general design community. A main goal has been to develop a framework which may be used to (1) gain a "big picture" view of the critical facets of compliant mechanism design, fabrication and use; and (2) to develop a simulation tool which may be used to generate new compliant mechanism designs and evolve them based upon user interpretation and modification of the mechanism's constraint and screw axis characteristics.

NOMENCLATURE

t	Time	minutes
E	Young's modulus	Pa
F	Force	N
K_G	Global stiffness matrix	---
S_D	Mechanism-actuator link matrix	---
δ	Mechanism displacement	mm
ε_p	Parasitic error	microns
Δ	Actuator displacement	mm

A FRAMEWORK FOR GAINING PERSPECTIVE IN COMPLIANT MECHANISM DESIGN / APPLICATION

This framework, shown in Figure 1, is used in the MIT Mechanical Engineering curriculum [3] to teach the fundamentals of mechanism (1999) and compliant mechanism (2002) design to undergraduate students and graduate engineers.

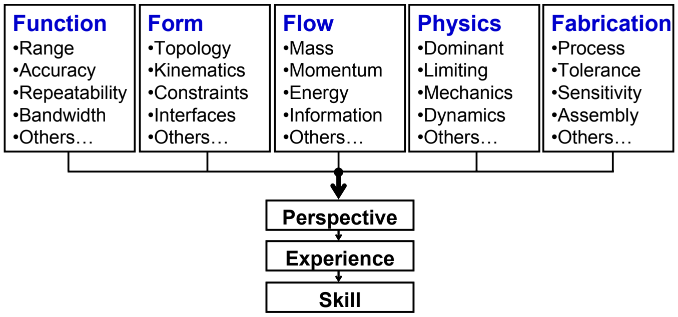


Figure 1: Compliant mechanism 5F framework

This framework is informally described at MIT as the 5 "Fs", with physics bent to an informal phonetic form -"F"ysics. We recommend reading the following descriptions with reference to the bulleted items in Figure 1.

FUNCTION:

It is important to understand functional requirements of a mechanism, as well as where, when and why this particular compliant mechanism is required.

FORM

Form provides links between function and flows, physics and fabrication. Form includes the geometry, constraints, interfaces and the kinematics of the compliant mechanism.

FLOWS

Three primary flows - mass, momentum and energy - affect changes in the mechanism's state. These flows must be understood and modeled via physics in order to understand how and why a compliant mechanism works.

PHYSICS

Physical laws are required to model these mechanisms and provide deterministic links between the other 4 "F"s.

FABRICATION

Fabrication sets practical limits on a compliant mechanism's available design space. This "F" is largely overlooked in education and mechanism research. This is unfortunate as it is difficult to measure the potential for impact that a compliant mechanism may have without quantifying how the work will be translated into a useful device which benefits society. It is therefore important for the compliant mechanism designer to understand how manufacturing processes, tolerances, characterization, rate, quality and cost affect compliant mechanism performance. The founding fathers of this science paid careful attention to fabrication issues.

The 5 F approach is useful because it helps us form a systematic way to understand how the geometry (Form), modeling (Physics), actuation-deformation (energy Flows) and manufacturing (Fabrication) are linked to a compliant mechanism's intended purpose (Function). Without such a holistic perspective, those who are new to the field have trouble identifying important issues and applying their engineering knowledge and skill to synthesize compliant mechanisms. Those who are armed with this perspective can systematically dissect a compliant mechanism problem into its important parts, identify the links between these parts and then apply their engineering knowledge and skill to a synthesis problem. In other words, they will know what they have to model/design/fabricate and why they must model/design/fabricate these mechanisms in a particular fashion.

THE ROLE OF SYNTHISIS AND SIMULATION IN COMPLIANT MECHANISMS RESEARCH/EDUCATION

Understanding how to model and synthesize a compliant mechanism requires skill, which in turn requires experience. We've studied the two main processes, education and research, by which engineers acquire experience. In traditional mechanism education, students "absorb" information and are led, mostly through paper-based problem sets, to gain knowledge and thought-based experience. In research, we observe, hypothesize/model, test and validate/disprove hypotheses. Experience is gained by hands-on activities such as simulation and experimental work.

Of the two processes, we find that a hands-on discovery process, adapted to the form shown in Figure 2, is a more effective means of gaining experience and skill with old mechanism designs (education) and new mechanism designs (research). The illustration is annotated with numbers which indicate the time sequence of steps by which the process is completed. Note, there may be iterative learning which occurs within the loop between steps 2 and 7. Step 5, simulation is carried out via the **Co**mpliant **Me**chanism **T**ool, CoMeT.

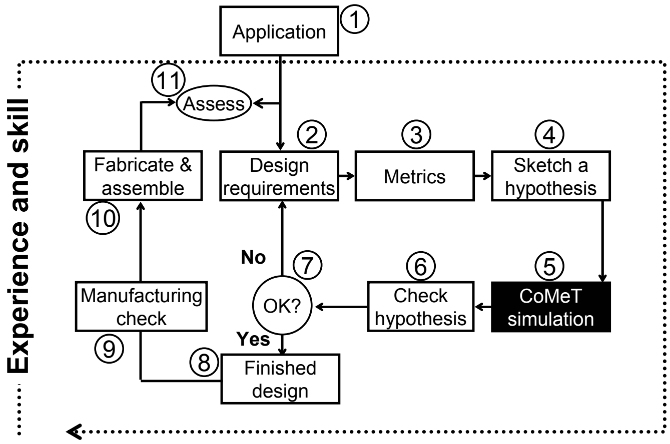
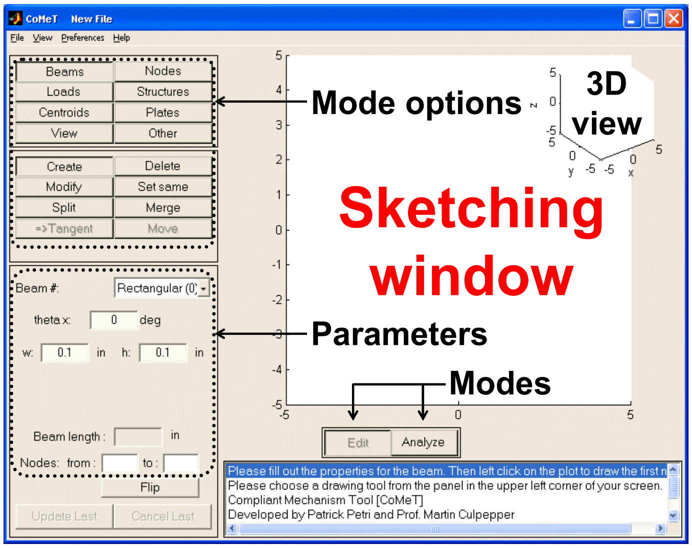


Figure 2: Discovery-based method of compliant mechanism synthesis and learning

CoMeT is equipped with a GUI, shown in Figure 3, which allows designers to define a mechanism's geometry, boundary conditions and loading conditions via hand sketches or keyed in values if desired [4]. The leftmost region in the display allows the user to input mechanism characteristics via button commands and/or keyboard input. The rightmost region is used to sketch mechanism geometry, constraints and loading conditions. This region emulates a "smart" piece of paper which records the designer's intent via sketch and returns analysis results in the form of a sketch. The mode options shown in Figure 3 are used to create geometry elements (e.g. curved/straight/tapered beams and rigid plates), set materials and apply boundary conditions. The parameter options set properties (e.g. beam length, width, thickness, curvature, taper, etc.…) via keyed-in values. Different modes are used to EDIT and ANALYZE the mechanism.



Please fill out the properties for the beam. Then left click on the plot to draw the first n

Please choose a drawing tool from the panel in the upper left corner of your screen.

Compliant Mechanism Tool [CoMeT]

Developed by Patrick Petri and Prof. Martin Culpepper

Figure 3: CoMeT GUI

CoMeT acts as a liaison between the designer and MATLAB, "conversing" with the designer via sketches and "conversing" with MATLAB via matrices. By conversing, we mean that CoMeT converts the designer's sketch into matrix equations which are analyzed by MATLAB. CoMeT then converts the MATLAB analysis back to a sketch (flexed mechanism) and numerical data (stresses, displacements and screw axis characteristics) which are interpreted by the designer. This liaison relationship and the analyses that may be performed are shown in Figure 4. Although CoMeT may be used on any Windows-based system, it is most effectively used via a Tablet PC (see right side of Figure 4) which enables the designer to sketch the mechanism, loads and constraints on the screen [5].

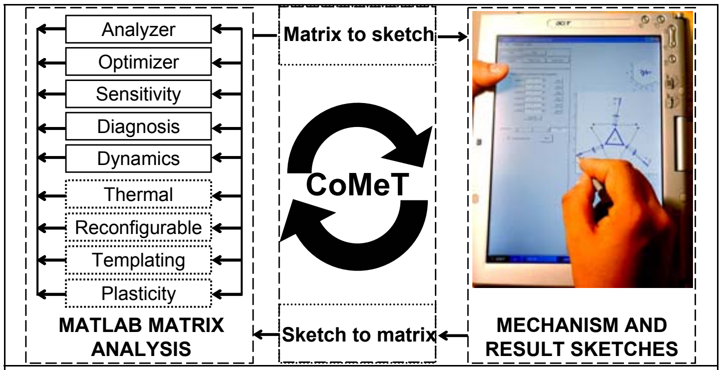


Figure 4: CoMeT analysis procedure

With CoMeT as a liaison, the mechanism design cycle in Figure 5A progresses more rapidly the corresponding FEA-based cycle shown in Figure 5B. This is due to the fact that FEA programs are analysis tools, not synthesis tools, and therefore not well-suited to rapid concept evaluation cycles. As a result, the iterative looping in Figure 5B may last hours for complex 2D or simple 3D mechanism concepts. For inexperienced users, the FEA method holds little intellectual reward. Likewise, experienced designers would prefer "sketching out" new designs on paper (e.g. CoMeT screen) rather than running FEA. In our tests, we've shown that CoMeT analysis of complex 3D mechanisms, such as compliant hexapods, requires less than five minutes.

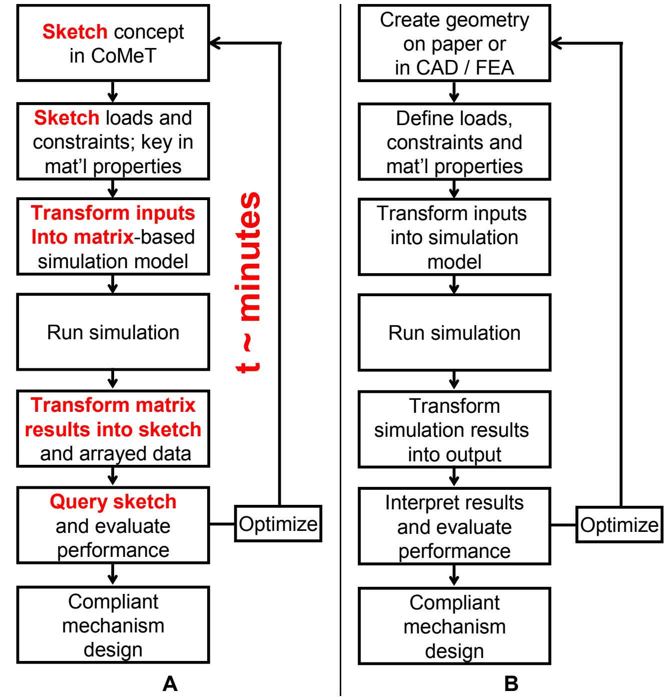


Figure 5: CoMeT synthesis (A) and FEA synthesis (B)

QUALITATIVE AND QUANTITATIVE RESULTS VIA COMET SYNTHESIS AND SIMULATION

CoMeT and traditional FEA programs provide qualitative deformation plots as visual feedback. Although this is helpful in developing an understanding of mechanism performance, it is not sufficient. To develop an understanding of how and why a new or old compliant mechanism works, a designer needs to form a quantitative link between design parameters and stage motions. This is necessary if there is to be an understanding of how performance is related to actuation inputs. CoMeT provides two types of quantitative information which FEA does not provide. This information is important to understanding how and why a compliant mechanism works:

(1) Screw axis characteristics: CoMeT displays screw axis position and orientation via a sketch and numerical data as shown in Figure 6 [4]. We use screw axes over instant centers as CoMeT is to be used in the design of 2D and 3D mechanisms with 6 axis motion capability. With this information, designers may generate designs and evolve them based on interpretation and modification of the mechanism's constraint and screw axis characteristics. As a result, they can study how constraint, compliance and their relationships to a mechanism effect how and why the mechanism works.

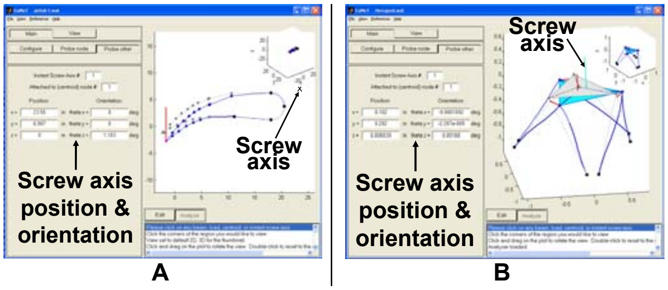


Figure 6: CoMeT models of compliant airfoil (A) and compliant 3D Hexapod (B)

(2) Input-output mapping: As part of the analysis procedure, a system of linear equations, including the global stiffness matrix, K_G, and a matrix which describes actuation, Δ, is solved. The results of this analysis provide a quantitative link, shown in Equation 1, between actuation inputs and mechanism performance outputs [6].

$$\delta = S_D \cdot \Delta \tag{1}$$

CoMeT provides the S_D matrix in numerical form so that it may be inspected for the relationship between mechanism response and actuation inputs. For example, Equation 2 shows results obtained from an analysis of a six axis compliant mechanism.

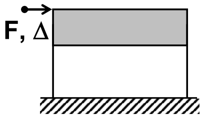
$$\begin{vmatrix} x \\ y \\ z \\ \theta_x \\ \theta_y \\ \theta_z \end{vmatrix} = \begin{vmatrix} S_{11} & S_{12} & S_{13} & 0 & 0 & 0 \\ S_{21} & S_{22} & S_{23} & 0 & 0 & 0 \\ 0 & 0 & 0 & S_{34} & S_{35} & S_{36} \\ 0 & 0 & 0 & S_{44} & S_{45} & S_{46} \\ 0 & 0 & 0 & S_{54} & S_{55} & S_{56} \\ S_{61} & S_{62} & S_{63} & 0 & 0 & 0 \end{vmatrix} \begin{vmatrix} \Delta_1 \\ \Delta_2 \\ \Delta_3 \\ \Delta_4 \\ \Delta_5 \\ \Delta_6 \end{vmatrix} \tag{2}$$

From inspection of Equation 2, we can see that the non-planar and planar motions of this mechanism are uncoupled respectively from actuators Δ_1, Δ_2, Δ_3 and Δ_4, Δ_5, Δ_6.

MODELING APPROACH AND ACCURACY

Small-moderate motion simulations are not as computationally intensive as large motion simulations, yet they are sufficient to identify a mechanism concept as either promising or inappropriate. As a result, we've designed CoMeT to use linear elastic deformation analyses. It is important to have a sense of the limits to this analysis, so we have provided Table 1 which shows less than 9% error between large and small displacements for the compliant elements listed in Table 1. This level of accuracy is sufficient to distill a list of possible design concepts down to a short list which may then be more accurately analyzed and optimized via FEA.

Table 1: Comparison of CoMeT and FEA results

	Cantilever		Four-bar	
	 Compliant beams: 1m x .05m x .05m		 Compliant beams: 1m x 0.5m x 0.5m	
	Small δ [microns]	**Large δ [mm]**	**Small δ [microns]**	**Large δ [mm]**
CoMeT	3.127	313	5.621	281
ADINA	3.122	289	5.587	265
	↓	↓	↓	↓
% Error	0.16	8.30	0.61	6.04

EXAMPLE: CONCEPT DESIGN TOOL IN RESEARCH

CoMeT has been used at MIT to synthesize 1st order designs of compliant mechanisms for six axis robotic Nanomanipulators and ultra-precision compliant mechanisms. The example in Figure 7 shows the development of a six-axis compliant mechanism from a CoMeT analysis (A) to a prototype mechanism (B) which was integrated with sensors and actuators to produce a six-axis Nanomanipulator system (C). The concept development time in CoMeT, 15 minutes, compares favorably with the hour required to analyze the initial concept in CAD-based FEA.

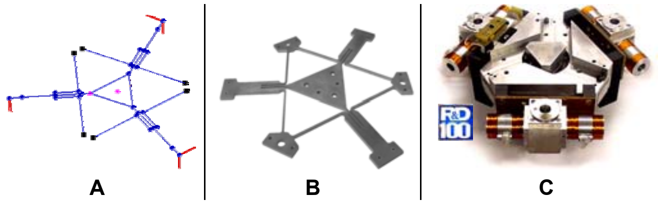


Figure 7: CoMeT model (A), HexFlex mechanism (B) and HexFlex Nanomanipulator

CoMeT is also used at MIT to synthesize new compliant mechanism concepts in:

(1) Reconfigurable compliant mechanisms
(2) Formed and folded compliant mechanisms
(3) Ultra-precision fixtures and Nanomanipulators

The framework provided by the 5F approach is being used to form the basis for a book on the design of multi-axis compliant mechanisms and a curriculum for designing compliant mechanisms in a graduate multi-scale systems design course.

EXAMPLE: USE AS A TEACHING TOOL

The 5F framework has been used in the MIT undergraduate curriculum to teach undergraduate students about compliant mechanism fundamentals. Once primed with the 5 Fs, and the requisite engineering knowledge, students used CoMeT as:

(1) An exploratory learning tool – The sketching and analysis components enable students to rapidly explore many designs and learn about screw axes, stress and stiffness. Students gain experience and skill in compliant mechanism design via the processes shown in Figures 2, 4 and 5.

(2) A design tool – In the Spring of 2003, CoMeT was used by freshman engineering students to design compliant *x-y* Nanomanipulators (Figures 8A and B) which rapidly traverse 30x30 micron mazes and race tracks [7]. In the spring of 2004, another class of freshman students designed these Nanomanipulators in addition to a MEMS mass-spring accelerometers (example shown in Figure 8C).

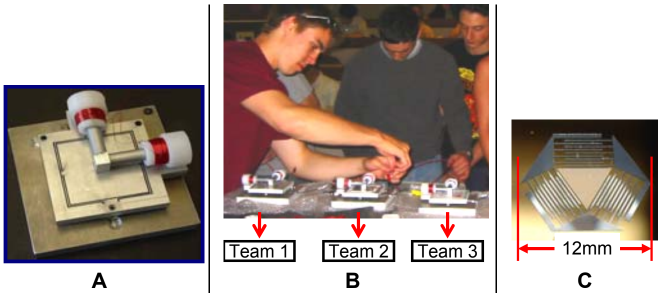


Figure 8: (A) X-Y Nanomanipulator; (B) Students preparing to race through a 30x30 μm race course; (C) MEMS device designed/fabricated by students

In closing this section on education, we can not overstate the importance of being able to have an active, archivable compliant mechanism (a saved CoMeT file). This capability has the following benefits:

(1) Researchers may share CoMeT files between themselves and with sponsors to describe compliant mechanism designs and discuss research results/ideas/concepts.

(2) Students may e-mail CoMeT sketch file(s) of their ideas to each other, thereby making the group project experience more productive outside of group meetings and via collaborative design software. They may also e-mail teaching staff the CoMeT sketch files to ask for help, or as a means of handing in assignments. The instructors may immediately see if the mechanism works by opening and analyzing the file.

Through item 2, we have identified the potential to use CoMeT as an educational assessment tool. We are currently forming methods which may be used to assess future developments in compliant mechanism education and to work with or assess other approaches to concept design via instant center/rigid body analyses [8].

SUMMARY

With this paper we have introduced a general framework which may be used with design knowledge and the CoMeT simulation tool to more rapidly synthesize and evaluate compliant mechanism designs. This approach increases the speed of learning while enabling rapid convergence on a good concept design in engineering research. Examples of CoMeT and 5 F uses in the MIT curriculum and in research were provided to demonstrate the utility of the tool/method. An academic version of CoMeT is publicly available [9].

ACKNOWLEDGMENTS

We would like to acknowledge the efforts of Mr. Patrick Petri who worked with Professor Culpepper to design, code and test the first version of CoMeT. We would also like to thank the Microsoft-MIT iCampus project and the MIT School of Engineering for supporting (in-part) the past and continuing development of CoMeT for pedagogical purposes. Our thanks to NSF for providing support to perform research in CoMeT modeling methods via grant 0348242, CAREER-Research and Education Plans for Modeling and Design of Fixtures and Six-Axis Manipulators for Nanomanufacturing. We also thank Ford Motor Company for providing technical and financial support for the MEMS accelerometer project.

REFERENCES

[01] Jones, R. V., "Instruments and Experiences," John Wiley and Sons New York, New York, pp. 22-122.

[02] R.S. Ball. "A Treatise on the Theory of Screws," Cambridge University Press, 1900.

[03] 2.000: How and Why Machines Work Course Web Site: http://psdam.mit.edu/2.000/start.html.

[04] Petri, P, "A Continuum Mechanic Design Aid for Non-planar Compliant Mechanisms," MS Thesis, MIT, 2002.

[05] RobotWorld iCampus project home page located at: http://pergatory.mit.edu/robotworld/.

[06] Culpepper, M. L. and G. Anderson, "Design of a Low-cost Nano-manipulator which Utilizes a Monolithic, Spatial Compliant Mechanism," accepted for publication in the Journal of Precision Engineering.

[07] 2.000 Nanomanipulator Design Project Web Site located at: http://psdam.mit.edu/2.000/project.html.

[08] Discussions with Prof. Sridhar Kota, University of Michigan, 10/31/03.

[09] Culpepper, M. L. and Soohyung K., "CoMeT-Lite Users Guide," PSDAM press (psdam.mit.edu/publications/).

APPENDIX: MAIN STEPS IN A COMET ANALYSIS OF SCREW AXIS LOATION IN A FOUR BAR MECHANISM

The four bar compliant mechanism in Figure 9A is proposed as a means to support and guide an optic through a rotation about its center. The mechanism is controlled by actuation Force F and must operate with low parasitic errors, ε_p, in x and y.

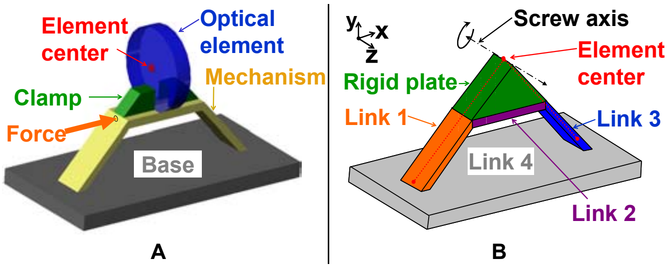


Figure 9: Mechanism application (A) and engineering model (B)

The maximum mechanism envelop and proposed sizes are shown in Figure 10. Design requirements are listed in Table 2.

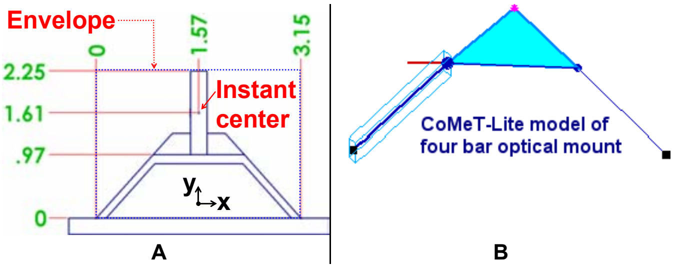
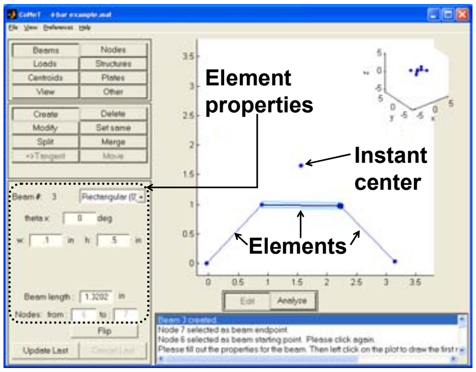


Figure 10: Geometry (A) and CoMeT model (B)

Table 2: Design characteristics and requirements

E	207	GPa	[30	Mpsi]
F	±4.45	N	[1	lbf]
ε_p	< 0.5	μm	[20	μ inches]
$\Delta\theta_z$	± 50	μradians	[0.014	degrees]

Step 1: Sketch compliant elements of mechanism concept and desired location of screw axis (instant center in 2D).

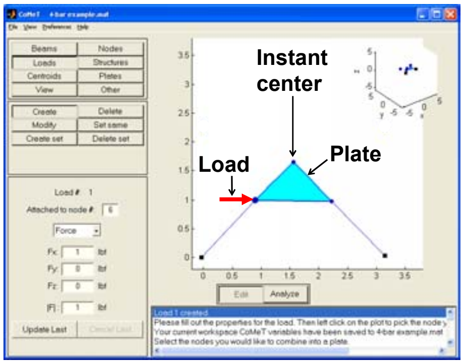


Beam #: 3 Rectangular
theta x: 0 deg
w: .1 in h: .5 in
Beam length: 1.3202 in
Nodes: from 6 to 7

Beam 3 created
Node 7 selected as beam endpoint.
Node 6 selected as beam starting point. Please click again.
Please fill out the properties for the beam. Then left click on the plot to draw the first r

Figure 11: Sketch compliant mechanism components

Step 2: Add rigid plate (plate emulates clamps/optic) and loads.

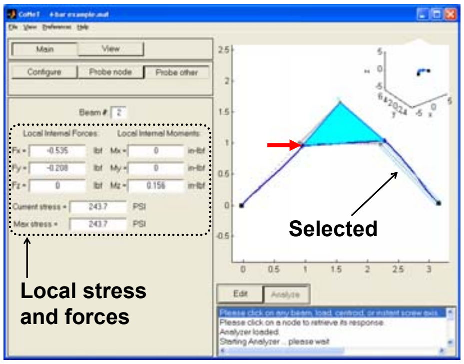


Load #: 1
Attached to node #: 6
Force
Fx: 1 lbf
Fy: 0 lbf
Fz: 0 lbf
|F|: 1 lbf

Load 1 created
Please fill out the properties for the load. Then left click on the plot to pick the node y
Your current workspace CoMeT variables have been saved to 4-bar example.mat
Select the nodes you would like to combine into a plate.

Figure 12: Sketch loads and rigid elements

Step 3: Analyze and query stress and reaction forces.

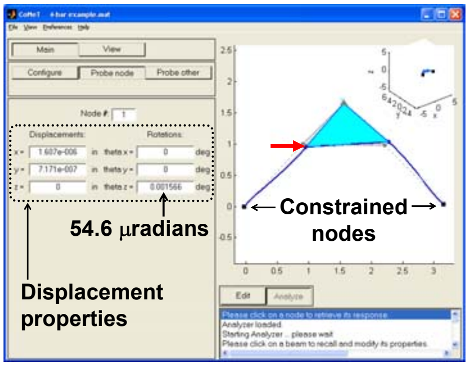


Beam #: 2
Local Internal Forces: Local Internal Moments:
Fx = -0.535 lbf Mx = 0 in-lbf
Fy = -0.208 lbf My = 0 in-lbf
Fz = 0 lbf Mz = 0.156 in-lbf
Current stress = 243.7 PSI
Max stress = 243.7 PSI

Please click on any beam, load, centroid, or instant screw axis.
Please click on a node to retrieve its response.
Analyzer loaded.
Starting Analyzer ... please wait

Figure 13: Analyze and query stress-reaction forces

Step 4: Query *x*, *y*, and θz to check range and parasitic errors.

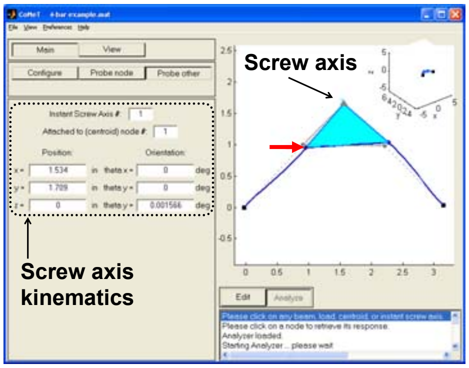


Node #: 1
Displacements: Rotations:
x = 1.607e-006 in theta x = 0 deg
y = 7.171e-007 in theta y = 0 deg
z = 0 in theta z = 0.001566 deg

Please click on a node to retrieve its response.
Analyzer loaded.
Starting Analyzer ... please wait
Please click on a beam to recall and modify its properties.

Figure 14: Query screw axis displacement

Step 5: Verify the accuracy of the instant center location.



Instant Screw Axis #: 1
Attached to (centroid) node #: 1
Position: Orientation:
x = 1.534 in theta x = 0 deg
y = 1.709 in theta y = 0 deg
z = 0 in theta y = 0.001566 deg

Please click on any beam, load, centroid, or instant screw axis.
Please click on a node to retrieve its response.
Analyzer loaded.
Starting Analyzer ... please wait

Figure 15: Query screw axis location

At this point, we could return to EDIT mode, make changes and reanalyze the mechanism.