A. G. Erdman
Department of Mechanical Engineering,
University of Minnesota,
Minneapolis, MN 55455-0111

Computer-Aided Mechanism Design: Now and the Future

The current status of computer-aided design of mechanisms is reviewed. The available software is described and several industrial examples are presented to illustrate current trends in the field of linkage design and analysis. Future strategies and CAD environments are also discussed.

Introduction

On the anniversary of the ASME Design Division's 50th year, reflections upon events that had a major impact on the division's technical history is quite appropriate. One may arguably suggest that the computer has played one of the major roles in changing the way we create mechanical systems. This paper will review the current state of the art of computer-aided mechanism design and look at needs for the future. The reader is directed to two references that in 1984 and 1991 summarized the then state of the art of mechanism design [1, 2]. This paper will attempt to build on those works but not be all inclusive in its coverage of mechanical CAD software. Instead, several examples will be shown to illustrate emerging features and creative uses of software. Since there is limited space, only a sample of features offered by each code will be provided, so the reader should not be tempted to make comparisons of products based on only that which is found below. The author has attempted to be complete on recognizing copyrights and trademarks.

Evolution of Software

Mechanism analysis and synthesis can be made more useful to the designer by having the computer carry out repetitive calculations. The engineer can then concentrate on the more creative aspects of the design process. Computer-aided analysis software is being used more naturally and frequently in mechanism design because computers have become more readily available and are more powerful, both in a numerical and graphical sense.

Application of the computer to mechanism problems has had a relatively short history [1]. Figure 1 shows some of the approximate landmark dates in the first forty-four years of computers applied to mechanisms. The 1950's saw the first introduction and availability of the digital computers in industry and engineering programs at universities. Dr. Freudenstein reviewed the computer programs developed for mechanism design prior to 1961 [3]: in 1951 Kemler and Howe introduced "perhaps the earliest published reference on computer applications in mechanism design; illustrates calculations of displacements, velocities, and accelerations in quick-return mechanisms" [4]. One of the early contributions which used the computer for linkage synthesis was that of Freudenstein and Sandor [5, 6], who adapted the graphical-based techniques suggested in 1876 by Burmester [7] and reformulated these for computer solution. The early 1970's saw a spurt in applications on the computer which are described below.

Advances in general-purpose programs for computer-aided kinematic and dynamic analysis of planar mechanisms provide powerful analysis capabilities. Substantial early contributions include IMP—Integrated Mechanisms Program [8], ADAMS®—Automatic Dynamic Analysis of Mechanical System [9], DYMAC—DYnamics of MAChinery [10] and DADS® Dynamic Analysis and Design Systems [11]. These

**COMPUTER - AIDED MECHANISM DESIGN
AN EVOLUTIONARY DEVELOPMENT**

1951 FIRST ANALYSIS SOFTWARE

1956 CAM AND FOLLOWER DYNAMICS

1959 KINEMATIC SYNTHESIS STARTS

1969 FIRST COMMERCIAL ANALYSIS PACKAGES AVALABLE

1971 FIRST USE OF INTERACTIVE GRAPHICS IN MECHANISM DESIGN

1979 FIRST INDUSTRIAL USE OF KINEMATIC SYNTHESIS

1982 INTEGRATION OF SYNTHESIS AND ANALYSIS SOFTWARE STARTS

1983 MICRO PROGRAMS EMERGE

1983 COMPUTER - AIDED TYPE SYNTHESIS

1985 PARAMETRIC MODELLING APPLIED TO MECHANISM DESIGN

1985 REBIRTH OF INTEREST IN OPTIMIZATION METHODS

1988 EXPERT SYSTEMS IN TYPE SYNTHESIS

1992 NEW ANALYSIS AND DESIGN PROGRAMS EMERGING

Fig. 1

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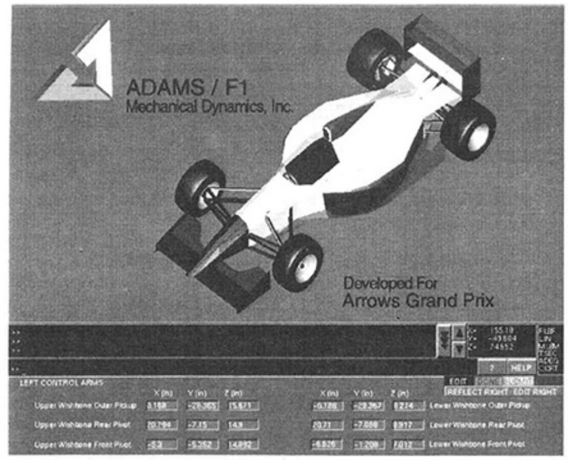
four packages originally resided on mainframe computers and solved both 2D and 3D multibody problems. As microcomputers and then workstations became available other kinematic and dynamic software has emerged. Some examples include MICROMECH© and KADAM—Kinematic and Dynamic Analysis of Mechanisms [12, 13], MCADA [14], ANALYTIX™ kinematic and dynamic packages based on variational geometry from Saltire Software [15, 86], Working Model—a 2D mechanical dynamics simulator that evolved from Interactive Physics II software [16], and Mechanica-Applied Motion®—a concurrent mechanism design and analysis program from Rasna Corporation [17]. There are university based packages that may also enter the market including MINNSKETCH©, [18] a Mac-like planar mechanical system sketcher from the University of Minnesota that interfaces with KADAM, and a graphic software environment for the computer-aided instruction package written by Nisbett [19, 20].

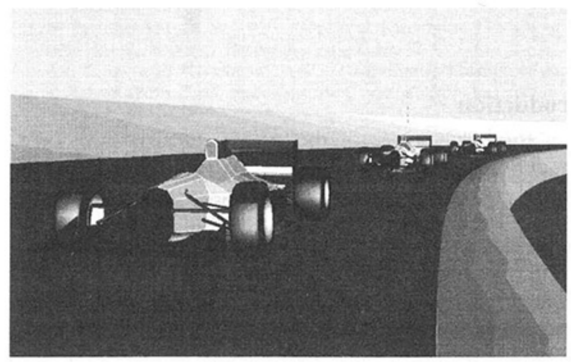
Kinematic synthesis software for design of planar mechanisms has evolved at a slower rate than analysis software. This is probably due to several factors: Often needs for initial solution configurations can be done either graphically or by starting with an old design. Secondly, it may seem more natural for an engineer to think of analysis as a method of solution rather than the seemingly more abstract synthesis options. Using an analysis code is analogous to building a physical prototype in the shop—which is a very traditional approach. Numerous designs can be tried in a software program for the same time in the shop. One can be fooled into thinking that all the design options are being considered. Analysis based codes require the user to prespecify (arbitrarily in many instances) the geometry (if not more variables) before kinematic or dynamic simulation can occur. After becoming accustomed to this method, the engineer will lose sight of the pitfalls of this approach. For example, a company that has a working philosophy of allowing little time for creative design will usually only produce incremental improvement and not obtain step changes in their products. Also, finding optimal solutions or even creating an understanding of the solution domain of the product is impossible without serious type and dimensional synthesis before traditional analysis.

A typical characteristic of synthesis software is the vast solution space of available solutions that is best displayed to the user by way of computer graphics and multiple windows. Since this type of computer environment was not generally available until the 1980's, analysis software had approximately a 30 year head start as a viable piece of the design engineering tool kit.



ADAMS/View™ interface tailored for Arrows Grand Prix to develop Formula-1 race cars.

Fig. 2



Arrows Grand Prix engineers visualize their designs under race conditions with ADAMS®.

Fig. 3

Analysis Software Examples

(*1*) As an example of sophistication of analysis software, Arrows Grand Prix International, a Formula 1 race team, has used ADAMS®, from Mechanical Dynamics, Inc. to find the optimum set-up for their race cars. The optimum set-up is the combination of adjustments to the suspensions, powertrain, tires, and aerodynamic surfaces that produce the fastest possible lap time. Arrows has used ADAMS/View™, (see Figs. 2, 3) the graphical pre- and post-processor for ADAMS which employs macros, custom menus, and custom panels. ADAMS is one example of a package that enables engineers to better understand their designs by providing three components: a parametric model, a design-of-experiment analysis, and a constrained optimization capability. The parametric model allows any parameter on the model to be changed simply by updating the data on a panel. Parameters may be virtually anything, including the position of pivot points, spring and damping characteristics, mass and inertia properties, aerodynamic forces, etc. The design-of-experiments capability systematically and automatically varies the design parameters and reports the effect of these changes against test criteria.

(*2*) Gas springs are versatile devices consisting of nitrogen-filled springs designed to deliver uniform force ranging from 30 to 5,000 newtons, making them suitable for a wide range of support, counterbalancing, tensioning, and damping uses. Since the force required of a spring varies as a result of its placement within an application, there are often several suitable springs for a given application. To investigate all the mounting position/spring possibilities for a customer using hand calculations of basic moments was taking Camloc (UK) Ltd. engineers at least three to four days and sometimes was not even possible. Using the ANALYTIX mechanism analysis package from Saltire, Beaverton OR, made it possible to quickly model a potential gas spring application on-screen and automatically solve force calculations to determine the appropriate spring for the specified load. To investigate different springs and mounting options, the user simply changes the model's geometry and the software automatically recalculates the problem. Now, in just one day, reports an engineering representative from Camloc, one can investigate as many spring possibilities as necessary to provide the customer with the least expensive, most durable gas spring for any application. Animation shows what angle the spring can move the object to, as well as what forces are being applied and where.

(*3*) A kinematically motivated problem was supplied by CADSI, Coralville, IA, where DADS was used to determine the extent of a four degree-of-freedom flight simulator's workspace requirements in order to correctly size the room in which it would be housed (Fig. 4). Historically, expensive physical prototypes of the "exact" simulator configuration were built without the true workspace requirements for the system. The maximum extent of the three-dimensional workspace was estimated using simplified hand calculations. These calculations, however, were up to 12 inches off, resulting in modification of room dimensions after the simulator was installed. An alternate approach was to put the physical prototype through its complete range of motion before installation and measure the locations of key points on the simulator by hand. Nevertheless, this method is tedious, time consuming and expensive. Because the simulator's size can vary depending on differing motion requirements, the simulator's design is often reworked. Specifically, the size of the cockpit on the simulator can vary as well as the sizes of the actuators used to support and drive the motion of the cockpit. The costs of building physical prototypes, therefore, increase tremendously.

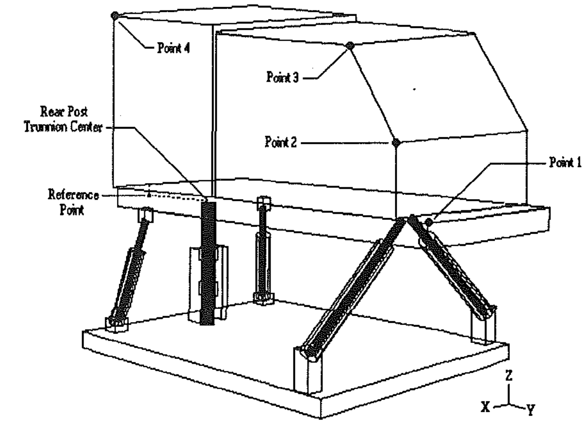


Fig. 4 DADS model of a flight simulator

The four actuators supporting the platform control the four degrees-of-freedom in the system. Each actuator is connected to both the platform and the base by spherical bearings to allow free rotation at each end. By extending the actuators to various lengths, several different combinations of yaw, pitch, roll and elevation can be achieved. There are limits on the stroke ranges of the actuators that need to be accounted for in the DADS simulations. Although this is a kinematic problem in nature, it is not possible to accurately model the simulator's actuators using kinematic drivers. Once the lengths of any three of the actuators has been prescribed, it is difficult to predict what the length of the fourth actuator should be. Due to the nature of kinematic calculations, if this fourth value is off by even a small amount, a kinematic analysis will not converge. By using force techniques, the simulator's entire motion envelope is examined in one run. Software prototyping can be taken even further by including the actual hydraulics and control systems into the simulator model. In this manner, full system performance can be analyzed without the need to build physical prototypes.

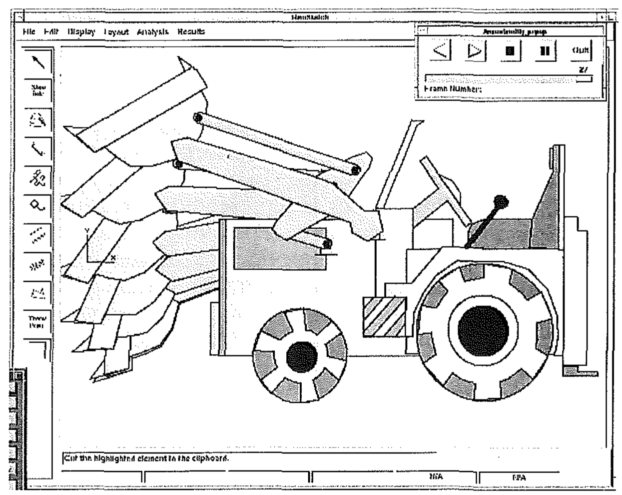


Fig. 5 Toy tractor animation created in MINNSKETCH

(*4*) A trend in analysis software is toward more user friendly input options. This is in contrast to the cumbersome numerically-based data input that was prevalent during the 1970's and 1980's. For example, icons representing mechanical elements such as rigid links, revolute and slider joints, springs and dampers can be placed with the mouse to generate chains of a complex mechanism in MINNSKETCH. Figure 5 shows a partial animation of a toy tractor that was created very quickly without the need for keyboard input.

Type Synthesis

The first step in the mechanism design process is type synthesis [21]. That is, choosing the best topology for a given task. No dimensions are implied at this stage—matching kinematic structure with function is the goal [22]. Computer aids for type synthesis may be found in rare circumstances for specific types of problems. Reported successes (or partial successes) in type synthesis tend to come from thesis work at universities or isolated industrial experiences. For example, the choice of "best" topology for a gear train has been addressed in [23, 24].

This author believes that the most critical stage of the entire mechanism design process is the choice of the most appropriate type of mechanism (e.g., four-bar, Stephenson III six-bar, eight link epicyclic gear train, etc.). There are many examples of the wrong choice of mechanism that have led to laborious efforts down stream to fix negative performance issues that were not perceived at the initial design stage. For example, a seven-bar, two-degree-of-freedom mechanism with two cam and cam followers was observed in an assembly machine of a Fortune 500 company. The hope was to increase the speed of this machine, reduce the cam follower "jump," and increase the life of its components. With little effort, a simple four-bar mechanism was synthesized to replace the more complex seven-bar. Besides satisfying the kinematic position requirements, the dynamic problems were eliminated by replacing cams, cam followers and springs with pinjoints.

Two approaches have been developed for type synthesis of mechanisms [22]. The first approach, still the primary source of mechanism design, is the creation of atlases of mechanisms [25, 26, 86] grouped according to function. The second approach involves either the abstract representation of the structure of the mechanisms or the symbolic representation of the functional aspect of mechanisms. This approach is more systematic but requires skill to envision how abstractions of potential topologies can be presented to the engineer in a meaningful way.

For analysis and synthesis purposes, a proper representation scheme for various types of elements of mechanisms is necessary. Franz Reuleaux [27], who pioneered the systematic study of mechanisms, developed a symbolic representation that was similar to the symbols used in chemistry for representing elements and compounds. Unfortunately, this scheme is cumbersome to use in synthesis and as Davies and Crossley noted [28], "The graphic qualities of the drawing are entirely lost." In more recent years, the notation put forth in Denavit and Hartenberg [29, 30], which is now known as the DH-notation in Robotics, is notable. However, this too is not amenable for automating the synthesis process.

Beginning in the mid-sixties, the abstract representation of kinematic structure was investigated with the aid of graph theory [28, 31–33]. Since then, the use of graph theory to represent the structure of kinematic chains and mechanisms has become dominant in the process of creative design of mechanisms.

Artificial intelligence techniques have been used to automate the process of mechanism type selection [e.g., 34–36]. However, most of the research is based on the graph theory approach to type synthesis and is generally restricted to planar mechanisms. Additionally, any approach based on graph theory has the drawback of not satisfying the function and operational constraints because the starting point for synthesis is primarily dependent upon the structural constraints. The only function that the graph theory approach takes into account is the desired degrees-of-freedom. Therefore, the enumerated chains are very general and purely topological.

A matrix methodology suggested by Kota et al. [37] forms one novel basis for a computable approach to type synthesis. In this methodology, the continuous design space of mechanisms domain is discretized into functional subspaces, and each subspace is uniquely represented by a conceptual building block. In the higher level of abstraction, each building block is represented by a motion transformation matrix and an operational constraint vector. In the lower level of abstraction, each building block is represented by a parametric matrix and a motion equation. The design task (desired behaviors) is represented by a motion transformation matrix and an operational constraint vector. By manipulating the matrices and vectors, the given task can be decomposed into subfunctions which is a series of building blocks. With the help of the lower level representation, a qualitative simulation of the motion of the synthesized mechanisms can be performed. The matrix scheme serves as a formal means to (*a*) represent and reason with the building blocks at different levels of abstraction, (*b*) generate alternate conceptual design configurations, and (*c*) facilitate rapid simulation of design concepts by readily connecting a series of building blocks.

Another recent new development of note is the work of Murphy et al. [38, 39] who developed a design methodology including type synthesis to compliant mechanisms. Many other notable approaches to type synthesis [e.g., 40–52] demonstrate the great potential of mathematical and heuristic-based methodologies. Time will be the test to see if one or more general methods will emerge as candidates for a CAD type synthesis module.

Dimensional Synthesis

The techniques of planar mechanism synthesis have been known since Burmester's time [7] but finding solutions required tedious calculations and drawings making the design process long and, at times, seemingly endless. The introduction of computers, with their quick computation times and always-improving graphics, freed designers of such tedious computation and allowed them to explore new and better ways of synthesizing a mechanism.

The first mechanism synthesis package to use interactive graphics—KINSYN—was developed by Kaufman in the late 1960s [53]. KINSYN I was a custom-built program at MIT and should be recognized as the major milestone in kinematic design. The digital computer alone took us halfway toward useful computer-aided design of mechanisms. Computer graphics for input and output as well as to enhance interaction in design decision-making was the second required ingredient. By the mid-1970s, several other software packages for synthesis and analysis became available. Software packages that were developed later include RECSYN [54], CADAM [55], SYNTRA [56, 57], LINCAGES-4© [58, 21], and LINCAGES-6© [59, 60]. LINCAGES-4 aids the designer in three- or four-precision-point synthesis of four-bar mechanisms offering many features that make the design process more procedural and efficient. LINCAGES-6, a related package started in the late 1970s by Chase et al. extends dyad synthesis to triad synthesis, allowing the design of single degree-of-freedom six-bar linkages.

In a recent communication, Dr. Kurt Luck from the Technical University in Dresden, informs me of several CAD programs developed under his direction. GISK, Graphical Interactive Synthesis of Mechanisms, has been developed for analysis and synthesis of several kinds of mechanisms, e.g., linkages, combined linkages and cam mechanisms. The maximum number of links is 17 and the graphical input for the computer is based on binary links. APPROX for personal computers is based on dyads and is able to analyze linkages which have as many as 12 links. The numerical input for the computer is based on the arrangement of several dyads. Mechanism synthesis can be done by using several optimization methods [61, 62].

Synthesis programs interact with the user in the opposite way as do analysis codes. In synthesis, the engineer specifies what is required of the mechanism and the program provides potential mechanism topologies that satisfy those design specifications. Whereas, analysis codes require the user to guess at the mechanism geometry (or other parameters) and then the user is shown how the mechanism performs. For example, in LINCAGES-4 from the University of Minnesota the engineer enters the values for the *X*- and *Y* coordinates of the path tracer point and the angular orientation of the coupler link. If a set of four design positions (precision points) is chosen, then a window graphically displays the cubic ground and moving-pivot design (Burmester) curves and superimposes a default linkage on top of them [color insert of 63].

Any other mechanism in the design space may be generated by pointing to any of the moving or ground pivots and pressing the mouse button. By holding down the button and moving the mouse, the selected pivot may be dragged along the curve, thereby moving the location of the pivot to the point at which the button is released. If none of the solutions are acceptable, then a new set of design curves (new infinite set of solutions) can quickly be generated. Precision points can be dragged to new positions and the angular orientation of the precision point can be changed by dragging the "handle" around the point in a circular motion. As with any modification, new design curves are quickly computed and redrawn on the screen.

Additional functions are available for designing a suitable linkage. For example, the Map of Solutions, a method of solution rectification, displays the entire design space for the current set of precision points. The color map shows the location of each Grashof region (crank, rocker, double rocker, etc.) for the set of prescribed positions. By moving the cross hairs in this window, different linkage types can be selected. As the cross hairs move, the linkage displayed in the Design Curves window also changes. Alternatively, as the pivots are dragged in the Design Curves window, the cross hairs are updated in this Map window.

Thus, this kinematic synthesis code displays the entire space of potential solutions based on the selection of design positions that the mechanism should pass through. In the four design position case, Burmester Curves designate ground and moving pivot constraint. If only three positions are chosen [64], then essentially the entire plane is a potential ground pivot and the corresponding moving pivots are found by standard calculations.

A new strategy recently reported in [65] allows the user to specify a range of input specifications and displays graphically the solution space of ground and moving pivot regions. This was inspired in part by the work of Kramer on selective precision synthesis [66, 67]. These works plus reference [68] begin to bridge between the fixed precision position method and the optimization based methods that may or may not have exact positions prescribed.

Solution Rectification. Solution rectification is the process of eliminating the undesirable solutions during the synthesis process, e.g., transmission angle, branching, dyads that traverse the precision positions in the wrong order, etc. Burmester-based synthesis codes are being made more powerful as further rectification is added to help segment the possible solution space in an intelligent way. Fortunately, a group of researchers [e.g., 69–80} are creating new theory and methodology each year. Although there is often a lag in implementation in software, the future should see smarter synthesis codes that block out Burmester-based solutions that do not satisfy one or more of the user's specified rectification. The strategy of this method is to keep the user in the loop to observe the reduction of the possible design space based on further rectification.

Optimization-Based Synthesis. Rasna's Applied Motion software [17] takes a different approach to mechanical system design. Previous parametric based systems such as COGNITION were numerically based requiring user knowledge of governing equations. In Applied Motion, models of the mechanism are generated in parametric form before solving in their analysis engine (based on SD Fast, which is founded in Kane's method). Thus, all mechanism parameters are variables that can be tweaked by way of optimization schemes. For example, link lengths, ground pivots, loads, etc., can be varied by the user to find an "optimal solution." Also, sensitivity studies are straightforward.

There are other general packages that can be used to model mechanical systems. For example, in TK Solver© and Mathcad, one can formulate equations representing either kinematic, dynamic and/or control modeling of mechanical systems. These types of programs often require a more sophisticated user, however, and lack the graphical capabilities of more customized packages. Recently, Analytix 3.1 has been linked to Mathcad 5.0 to allow a geometric value calculated in Analytix to show up as a variable in a Mathcad equation and visa versa.

Lincages-4 Example—Redesign of a Camera Opening Mechanism. Reference [81] reports on the redesign of an initial camera opening mechanism concept that had some potential problems. Many design and manufacturing constraints both narrowed down the solution space and made it more difficult to find an optimal solution. One of the goals for the redesigned mechanism is to accurately position the mirror angle in the open position of the camera. This angular position should be as independent as possible from the angular position inaccuracies of the shutter-housing due to manufacturing tolerances.

The redesign effort of the initial concept was warranted due to the potential second degree of freedom nature of the initial concept (see Fig. 6). If, for instance, the user were to hastily close the camera, the slider (body 7) could prematurely slide down the slot in the lower link (body 4) once the available torsion between the shutter-housing and the shutter link is exceeded. Once the slider prematurely slips the mechanism gains a second degree of freedom. The motion of the mechanism is then indeterminate and a catastrophic failure of the shutter-housing hitting the tip of the mirror could occur.

After the type synthesis step, a six-bar mechanism, which is a special case of Stephenson III with copivotal grounded links was chosen. Based on four design positions highly

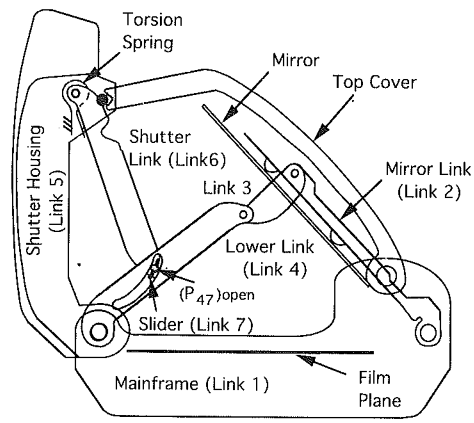


Fig. 6

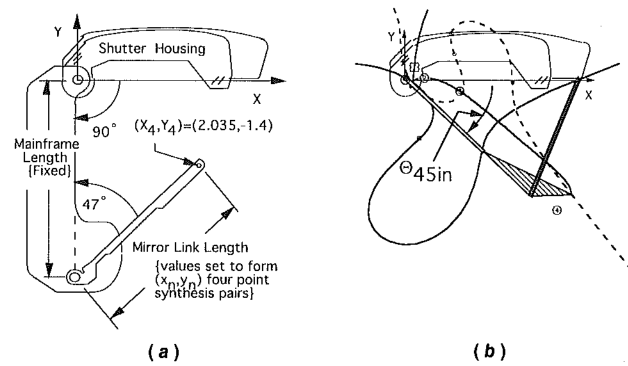


Fig. 7

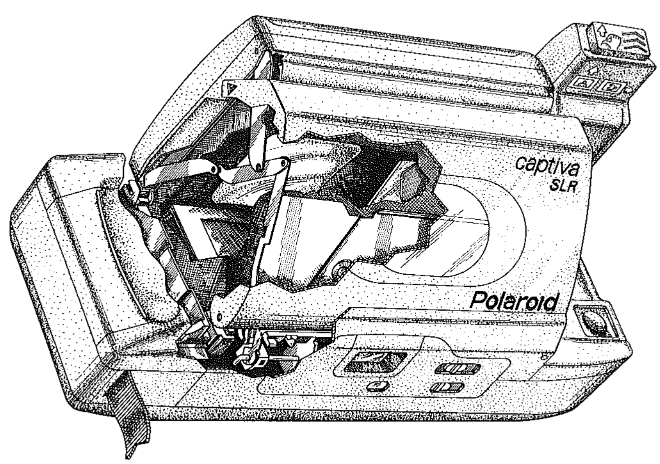


Fig. 8

constrained by camera size, optical, and mirror/shutter-housing interference avoidance, computer assisted mechanism synthesis design strategies were developed. Kinematic inversion provided a breakthrough for handling three of the five initial design and manufacturing constraints, and helped convert a concept into a near final design. LINCAGES-4 was used to synthesize a sub-four-bar of the six-bar concept based on path tracer point of the design positions of the mirror link relative to the shutter housing (shown in Fig. 7). Four design positions were inserted into the software yielding an infinite set of ground and moving pivots (solid and dashed curve, respectively). The ground pivots shown are where the Burmester Curves cross the shutter housing. The final optimized six-bar solution (see Fig. 8) has ideal mirror dwell characteristics in both the open and closed positions. The implication of design and manufacturing strategies described in this paper led to the successful release of the Captiva Camera. It is deemed doubtful that an acceptable linkage solution would have ever been found without the use of LINCAGES-4.

Spatial Mechanism Design

The Burmester dyad approach to planar synthesis has been found to be extendible to spatial dyads using very similar solution strategies by McCarthy et al. [e.g., 82, 83]. The discoveries of Loerch [64] find direct analogy in spherical and spatial dyads. This breakthrough in thinking that has evolved over the past six years may lead to a more general dyadic synthesis methodology covering many 2 and 3D mechanisms.

Design of mechanisms that move in 3D provide a visual challenge, even with the planar graphical methods described above. Myklebust [84] and McCarthy [85] with SPHINX, a work station based spherical four-bar mechanism design package, have experimented with three-dimensional interfaces for designing spatial mechanisms. Now virtual reality (VR) holds some promise as an aid to spatial mechanism design.

VR is emerging as a new computer-based technology which allows users to be immersed in an artificial computer-generated world, and interact with the virtual world as if it were real. Physical movements of a user's body, head, and hands are replicated in the virtual world and coordinated with a head-mounted graphical display to create the illusion of presence in, and interaction with, the virtual world. In addition to sight, other powerful virtual sensory mechanisms are emerging such as those for tactile and aural feedback. In recent years these innovations, combined with the rapid advancement of computer hardware and graphics software, have driven VR from a research curiosity toward application as a serious new tool in a variety of fields.

Virtual reality has applications to mechanism design, especially spatial mechanisms. Because of their nature, spatial mechanisms occupy a three-dimensional design space. Design of these mechanisms is difficult for two reasons: specification of the input design parameters and constraints, and verification of the resultant design. Design in a virtual reality environment allows the designer to "reach out" and place pivot points, coupler links, etc. in a three-dimensional computer-generated space. Thus there is a potential of a virtual tool box available to build a virtual prototype. Once the final design has been achieved, the designer can animate the mechanism to verify the motion of the design. In addition, while the mechanism is moving, the designer can "walk" around the space and view the motion. Surrounding constraint surfaces can be present and collision detection can be implemented to indicated difficulties with the design.

Dr. J. Vance from Iowa State (who provided input for this section) has developed a prototype VR system in which a spatial mechanism of an old car radio was modeled in IDEAS software and then input into a World Tool Kit program. The user sees through a textured mapped case first, then can "walk into" and eventually manipulate the view of the mechanical system's motion.

With the development of these new techniques in visualization comes unique opportunities to improve the process of designing spatial mechanisms.

Future Need

As discussed above, design and manufacturing engineers currently have a large choice of software tools to aid in the creation of new mechanical systems. The great majority of software addresses kinematic and dynamic analysis needs. This is not surprising since there are numerous mature methodologies for solving the multi-body dynamics problem. Software for kinematic synthesis is less available and less mature.

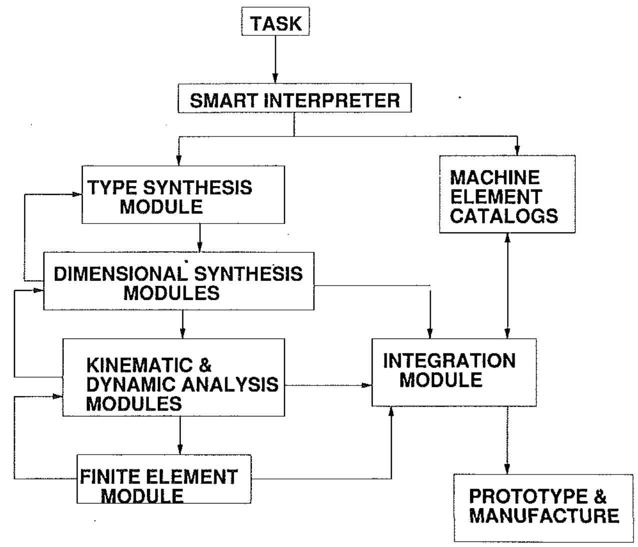


Fig. 9

One can dream about an ideal set of software tools for the machine designer. All modules must either be connected together or easily pass data back and forth. Figure 9 shows one embodiment of such a strategy. A specific need or task would pass through an intelligent interpreter that would determine if there is a "stored solution" for the particular problem or if more in-depth synthesis would be required. For example, the user may be directed to a flat-faced cam follower system for a low speed function generation task where high precision is important and rotary to linear motion is required. These types of solutions would be found in the machine element catalog section which would be a storage bank (perhaps a CD ROM) of known mechanisms or mechanism components that are "off the shelf" variety. Also, available would be vendor supplier parts lists of critical components. For tasks that do not find an appropriate solution in the machine element catalog, the smart interpreter would send the problem to the type synthesis module. Here analytical tools would be used to match tasks to mechanism types. Topological decisions are made at this stage relying on heuristics, polynomial matching, graph theory, data bases or other mathematical methods. Best efforts would be made to place the user in the correct "ballpark," but the "exact seat" will be found only after dimensions are placed on the mechanical system. This will be accomplished in either the machine element module (for stored solutions) or in one of the dimensional synthesis modules.

In the future one can hope for either a general purpose mechanical system dimensional synthesis package or a series of separate but connected software tools that are optimized for each class of mechanical systems. A truly universal dimensional synthesis module would cover four-bar, six-bar and other single degree-of-freedom planar linkages, cams, gear trains, spherical mechanisms and spatial closed and open loop mechanisms. Each of these should include some method (such as three dimensional graphics or virtual reality tools) of allowing the user to look at the entire solution space that satisfies the stated task in ways that are intuitive and instruct about solution sensitivity to design parameter specification. This author prefers graphical displays while others may prefer the computer to perform optimal searches, shielding the user from being "in the loop." Perhaps some hybrid system is best and each class of problems may dictate the best strategy.

Once kinematic solution(s) are found, dynamic analysis and dynamic synthesis modules would subject the potential solutions to more constraints. Ideally, all parameters (kinematic, dynamic controls, stress/fatigue using finite element methods, and manufacture) would be considered simultaneously, but the user should be fully aware of the consequences of each design constraint and the sensitivity of solutions to these chosen constraints. A rapid prototyping system could then produce the final solution in a form that can be held and inspected by the user prior to actual production of the final design.

Future mechanical design software will hopefully move in the direction indicated above. Users can have a tremendous influence on software developers if their need is stated clearly. Future mechanical design software should have the following characteristics: an easy to use, logical methodology to input design specifications and geometry; some type of kinematic synthesis module so that users do not have to arbitrarily choose any system variables; a method to alert or display to the users the size of the solution space they are dealing with; animation at all logical steps in the design process; integration with as many other software tools as possible; methods of sensitivity analysis (to tolerances and/or changes in system variables) and direct connection to either rapid or conventional prototyping. On the user end, designers and engineers who are responsible for mechanism design must already be familiar with the software tools when a need arises. Experience shows that there is never enough time to both learn the software and conduct engineering design when the boss says, "get the job done."

Acknowledgments

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