2 Computer Aided Mechanism Synthesis: A Historical Perspective

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Abstract. The age of computer aided mechanism synthesis began in the late 1950's, as Freudenstein & Sandor published the first paper on the topic [14]. Many exciting developments occurred over the next 60 years, resulting in the development of multiple intriguing mechanism synthesis packages at several leading research institutions.

This paper provides an historical overview of the developments in computer aided planar linkage synthesis in the time window of 1955 to the present. The origins and legacies of those packages are reviewed. Key contributions to the field by Waldron and his associates are recognized.

1 Introduction

The design of many machine elements is accomplished by developing the input-output equations and solving for the design parameters by inverse methods. When linkages are involved, however, the solution space is usually so nonlinear that it is difficult to develop viable solutions simply with inverse techniques. Therefore, special approaches to linkage synthesis problems which incorporate the constraints directly into the synthesis equations have been developed.

The majority of linkage synthesis problems can be classified in one of four categories: function generation, motion generation, path generation, and crank-rocker synthesis [43]. Of these four types of problems, function generation and crank-rocker synthesis can usually be approached using relatively simple special purpose

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programs or they can be recast as special case motion generation problems. Therefore, the most difficult problems tend to be motion generation and path generation, and this is where much of the effort in developing robust computer-aided design (CAD) programs has been concentrated.

Since computers became available in universities in the late 1950's, much time and effort has been expended by engineers and computer scientists to develop design software that will simplify the linkage design process. Most of the early work was done by relatively young faculty members who had an intense interest in kinematics and were intrigued by the new tool that computers offered. A few of these efforts led to the development of software packages that were relatively widely used and even commercialized.

This paper will provide a historical overview of the development of computer aided mechanism synthesis programs. The scope is limited to planar linkages. Although path generation will be mentioned because it is covered by some of the software packages, the main emphasis in the paper will be on CAD approaches to motion synthesis.

The methodology of synthesizing linkages using precision precisions is contrasted with optimization methods in Section 2. Problems that can arise during precision position synthesis are also introduced. Early linkage synthesis programs were all developed at research institutions; they are reviewed in approximately chronological order in Section 3. More recent efforts are typically developed as extensions to existing commercial CAD software; they are described in Section 4. Some speculations on the future of computer aided linkage synthesis programs are offered in Section 5. Conclusions are in Section 6.

2 Technical Approaches Used in CAD Software

Motion generation has been approached using two fundamentally different approaches. In the first, a large number of positions of the moving plane (coupler) are specified, and the best linkage which moves the coupler through the positions in an approximate sense is determined through a mathematical optimization process (for example, see [25]). In this approach, the coupler is unlikely to pass through any of the positions exactly. This approach is based more on optimization concepts than on kinematic concepts.

The second approach, which is emphasized in this paper, is based on precision position synthesis. In this approach, the linkage is designed such that the coupler passes through a modest number of prescribed positions exactly. This approach usually results in multiple solutions. Optimization may be used ultimately to select the best linkage from the domain of possible linkages; however, optimization constitutes a secondary process.

In the precision position synthesis approach to motion generation, 2-5 positions of the coupler relative to the reference link can be specified. The two position problem yields three infinities of solutions. Even with five positions, multiple solutions can result.

The definitions of circuits and branches of linkages proposed in [5] will be adopted in this paper: A circuit is defined as all possible orientations of the links which can be realized without disconnecting any of the joints. If a circuit contains stationary configurations, a branch is defined as a continuous series of positions on the circuit between two stationary configurations. Using these definitions, four-bar linkages satisfying the Grashof criteria have two circuits while those that do not have one. The single circuit of a non-Grashof four-bar linkage has two branches. A crank-rocker or double-crank has two circuits, but since they do not contain stationary configurations, branching is irrelevant. The two circuits of a rocker-crank or Grashof double-rocker both contain two branches.

Solutions generated using precision position based synthesis methods are not useful if the precision positions fall on different circuits. They are often not useful if the precision positions fall on different branches. In addition, solutions may be defective because they pass through the precision positions in the incorrect order [39]. In some situations, the designer is interested only in solutions that have fully rotatable driving cranks (for example, [16]). Basic precision position synthesis methods leave it to the user to determine whether a solution suffers from any of the possible kinematic defects. Some of the sophisticated synthesis packages described in Section 3 are programmed to automatically sort out desirable solutions from defective ones.

In the majority of cases, even after eliminating solutions with circuit, branch, order, or crank rotatability defects, the designer must still choose among multiple solutions. She may do this by explicitly identifying additional constraints or by using objective or subjective techniques for selecting among the various choices.

One of the main features of CAD software is to help the designer choose the most desirable solutions. The main objective of all software that is to be used by technician level designers is to provide an environment that will allow the designer to obtain a good or near optimum solution quickly without needing an in-depth knowledge of theoretical kinematics. As will be discussed when individual software packages are described, programs provide this assistance by graphical interfaces that guide the designer through the process, by incorporating sophisticated mathematical optimization routines, or by incorporating pattern matching and/or knowledge based systems that narrow down a large number of solutions to a small number (perhaps one) that the user can easily evaluate.

3 The Early Years of Software Development

Freudenstein and Sandor [15] were the first to publish a paper which utilized a "digital computer[1]" to synthesize a linkage. Their program was set up to design four-bar linkages for path generation with prescribed timing for five precision positions. Their program was written for a specific computer, the IBM 650, but it likely would have been adaptable to any similar machine which used the same programming language.

[1] At the time of publication, analog computers were commonplace.

Freudenstein and Sandor's pioneering synthesis program was also the first to attempt to identify the best of multiple synthesis solutions. Up to four dyad solutions exist for the five-point synthesis problem. These can be combined to create up to six four-bar linkage solutions, which can be extended to twelve by constructing cognates of these linkages[2]. Their program automatically selected the best solution based on a quality index comprised of the ratio of the shortest link length to the longest link length times the range of the driving crank rotation. The program also performed a displacement analysis of the solution for evenly spaced increments of the driving crank, establishing a precedent that would be followed by several later programs.

Freudenstein and Sandor [15] provide several examples of how the synthesis program presented in [14] can be utilized to solve several related synthesis problems. Specifically, they demonstrated the synthesis of a four-bar function generator, a geared five-bar linkage, and a two-degree-of-freedom seven-bar linkage. They also provided a more detailed theoretical derivation of the five precision position solution. They suggested generalizing Burmester theory to the case of observing the motion of one moving plane relative to another, thereby anticipating the formulation of triad synthesis methods [4].

Kaufman pioneered mechanism synthesis using interactive computer systems [26]. His "KINSYN" program was the first to utilize an interactive input device, a data tablet, and an output display, a dynamic cathode ray tube (CRT), to enable a user to interact with the program while it was running (see Fig. 1). The early versions of the program described in [26] utilized a custom hardware system, so it was only operable at its development site (MIT). It featured an impressive list of synthesis capabilities, including motion generation for two, three, four and five precision positions. The program was capable of designing linkages with slider joints in addition to revolute joints. It was capable of analyzing tentative solutions to determine their Grashof type, circuit, branch, order of traveling through the prescribed positions, transmission angle, and acceleration. It could animate solutions on the display device, including multi-loop extensions to the basic four-bar solution.

A later version of KINSYN, "Micro-Kinsyn", was re-designed to run on an Apple IIe personal computer augmented with a custom input module [18]. Unfortunately, it did not prove feasible to keep the program current with the rapid pace of computer hardware development at that time.

Erdman and associates [11] developed another early interactive mechanism synthesis package, the Linkage Interactive Computer Analysis and Graphically Enhanced Synthesis Package (LINCAGES)[3]. LINCAGES overcame the need for specialized hardware by utilizing either a commercially available "storage tube"

[2] Up to 18 solutions were created if the user chose to release the prescribed timing constraint.

[3] The third author recalls that the LINCAGES project was initiated only because KINSYN was not available outside of MIT in its early days, so the creation of LINCAGES was necessary to expose University of Minnesota students to Kaufman's groundbreaking interactive synthesis strategy.

Fig. 1 The KINSYN III hardware. The human user was utilized as an integral part of the synthesis procedure. The user observed the current state of the design on the CRT screen and input directions for continuing the synthesis by way of a data tablet. As such, KINSYN may have constituted the first interactive computer aided engineering program. (Published by ASME, FIGURE 1 from [26], Journal of Engineering for Industry, Vol. 99 No. 2, by Rubel, A. J., and Kaufman, R. E., 1977.)

graphics display[4] or a teletype for both input and output to a mainframe computer operating in time sharing mode. While the teletype option was slow and had poor resolution, it made the program accessible to venues where linkage synthesis tools had been previously unavailable. The early LINCAGES program had the capability to synthesize four-bar motion, path and function generators for three, four or five precision positions, although the four point capability was developed more extensively than the other options.

Both the centerpoint curves and circlepoint curves were displayed for four point solutions, and the user could interactively select from either one. Solution dyads were parameterized according to the rotation of one of the dyad vectors between the first and second precision positions, β_2 (for example, β_{2A} in Fig. 2). While not ideal by way of intuitive understanding[5], this parameterization enabled the user to explore the entire domain of solutions associated with four point synthesis. This was done by creating a table of tentative solutions where a range of β_2 values for driving dyads was

[4] Storage tube displays were popular from about 1977-1987. They were relatively affordable interactive displays. Once a line or character was written to the screen, it would remain on the screen until the entire screen was erased, usually a matter of a minute or more.

[5] The matter is further complicated by the fact that each β_2 value has two different dyads associated with it; for example, see [3].

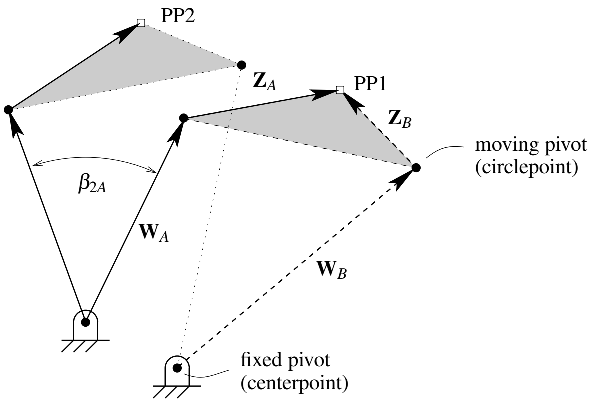

Fig. 2 Four bar motion generators are synthesized by combining two dyads, $(\mathbf{W}_A + \mathbf{Z}_A)$ and $(\mathbf{W}_B + \mathbf{Z}_B)$. β_{2A} represents the rotation of vector $\mathbf{W}_A$ from precision position 1 to precision position 2. LINCAGES utilized the β_2 value of a dyad to parameterize all solutions to the four precision position synthesis problem.

represented in the rows and a range of β_2 values for follower dyads was represented in the columns (see Fig. 3). The minimum transmission angle at the precision positions, if the solution was free of the branch or circuit defect, and the maximum link length ratio was calculated for each combination of two dyads. The user could then identify an attractive solution by selecting a solution from this table.

Filemon [13] authored a seminal paper on identifying portions of Burmester curves for four precision position synthesis which would produce linkages which have kinematic defects. Specifically, she identified sections of the curves where the precision positions could be reached in the correct order by continuously rotating a selected crank link, and where the follower link would not change position from above the ground link to below the ground link. The latter would lead to either a circuit or branch defect in the solution.

Filemon did not develop a computer based synthesis program. However, her pioneering work inspired Waldron and his associates to greatly extend and refine her work to the point that it could be utilized for computer assisted linkage synthesis. Waldron coined the term "solution rectification" to describe methods to eliminate spurious solutions in an a priori manner. Ultimately, he developed techniques for solution rectification for four-bar and slider-crank linkages for 2-5 precision positions. Rectification of the circuit and branch problem is addressed in [37, 40, 44, 45]. Identifying linkages that traverse the prescribed positions in the correct order is addressed in [39, 40, 44, 45]. Identifying linkages with a specified Grashof type is addressed in [38, 42, 34]. Controlling the transmission angle at the design positions is addressed in [35, 46].

The Rectified Synthesis, or RECSYN, program of Waldron and associates [6] implemented their solution rectification methods in a powerful four-bar synthesis program. While set up for synthesis for motion generation, path and function

TABLE OF LINKAGE PARAMETERS

MINIMUM TRANSMISSION ANGLE — N.NN / N.NN — MAXIMUM LINK LENGTH RATIO

INPUT SET 2						
90.	TOG 9.9	T-RR 2.7	T-RR 17.5	T-RR 2.5	T-RR 2.5	T-RR 3.1
75.	TOG 9.8	3.6 2.3	R-R 16.9	R-R 2.4	T-RR 2.4	T-RC 3.0
60.	R-R 9.2	15.4 2.2	14.8 16.8	R-R 2.4	R-C 2.4	R-C 3.0
45.	17.7 6.2	37.1 2.7	R-R 26.2	R-R 3.8	R-C 3.8	R-C 4.6
30.	35.0 2.2	R-R 4.1	R-R 39.2	R-R 5.7	R-R 5.6	TOG 6.9
15.	R-R 2.3	R-R 6.6	R-R 62.8	BRAN 9.1	BRAN 9.0	BRAN 11.0
	45.	60.	75.	90.	105.	120.

FOLLOWER SET 1

Fig. 3 The "TABLE" function in LINCAGES enabled the user to quickly explore the entire solution space for promising solutions. The solutions in the matrix correspond to selecting a driving dyad with a β_2 value shown in the left column and a follower dyad with a β_2 value in the bottom row. The top number in each matrix entry represents the minimum transmission angle at the precision positions, if one exists. The lower number indicates the maximum link length ratio of the solution. A top entry of "R−R" indicates that the solution has changed branch between precision positions, while "BRAN" indicates that the solution has changed circuit.

generators could also be synthesized by applying kinematic inversion. The original RECSYN was designed for storage tube type interactive displays, and it exploited an evanescent imaging option[6] to dynamically "rubber band" links corresponding to each synthesis step to the interactive selection cursor.

RECSYN had a very well developed three point synthesis option, as Waldron recognized the common need for three point solutions to practical problems. The user was guided to select a circlepoint defining a follower dyad prior to a driving dyad. Regions where placing a circlepoint would lead to a relative rotation between the coupler and follower greater than 180° were automatically deleted, as this would lead to solutions having a circuit or branch defect. Waldron created a method which he called the modified Filemon construction[7] to identify portions of the plane where circlepoints for the driving dyad could be selected without causing the transmission angle to change sign. Once a follower dyad was selected, the graphics display was updated to present the results of this construction, and the user was guided to select a driving dyad circlepoint in the remaining allowable regions. The Grashof type of a grid of sample solutions was also displayed in the allowable region. A final useful feature of the three point option was the display of the slider point circle. In addition

[6] The evanescent image was a dim dynamic image superimposed on the static background written to the storage tube display.

[7] The method was inspired by a similar construction applied to centerpoints by Filemon [13].

to its utility for designing slider-crank linkages, this circle also enabled identifying portions of the circlepoint plane where link length ratios tended to be poor.

The four point solution was equally well developed (see Fig. 4). The display for selecting the follower circlepoint would remove portions of the circlepoint curve where the relative rotation between the coupler and follower would exceed 180°. Once a follower link was selected, Waldron's modified Filemon construction was applied to identify portions of the circlepoint curve where moving pivots for driving dyads could be selected without causing the transmission angle to change sign. Finally, the circlepoint curve was subdivided so as to indicate the order of rotation of the driving crank as it passed through the precision positions[8]. RECSYN also included a five point option, but performing a comprehensive check of the small number of five point solutions proved more efficient than attempting to adapt solution rectification to this problem.

RECSYN was later extended to include several additional useful features [31]. Two position synthesis was added, where Waldron's modified Filemon construction was performed to help select a driving circlepoint. The program was modified to handle solutions for parallel precision positions where possible. A unique enhancement consisted of augmenting the modified Filemon construction to include a "starburst" of lines through the selected circlepoint that indicated the highest deviation angle reached at all the precision positions. Other enhancements included the addition of optimization techniques to choose the best linkage for 2, 3, and 4 position synthesis based on the link length ratio and transmission angle [1, 28, 33]. The optimization approach was later extended to allow the two middle positions in a four-position problem to vary within a given tolerance range to extend the range of the design parameters in the optimization process [36].

The MECSYN program [23, 30] was developed in the same time frame as KINSYN and LINCAGES. MECSYN is notable for two reasons. It constituted the first program to be capable of designing multi-loop mechanisms. The program had the ability to kinematically invert[9] basic dyads, which enabled it to synthesize Stephenson six-bar linkages and other mechanisms more complex than simple four-bar linkages [22][10]. Second, it was the first program capable of synthesizing linkages for multiply separated positions[11]. Four or five multiply separated position problems could be solved.

The SOFBAL program [32] originated with the same group that developed MECSYN. SOFBAL constituted a blend between Burmester theory based synthesis methods and synthesis by optimization. Burmester theory was used to generate circlepoint and centerpoint curves for four positions. However, the user did not directly select solution linkages from the Burmester curves. Rather, the curves were

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[8] Features varied between versions. The version illustrated in Fig. 4 does not appear to implement this feature.

[9] Kinematic inversion refers to the ability to change the link which is assumed to be attached to ground.

[10] MECSYN is cited as being a work in progress in the conclusion of this paper.

[11] Multiply separated positions enable specifying velocity and other higher derivatives at specified precision positions.

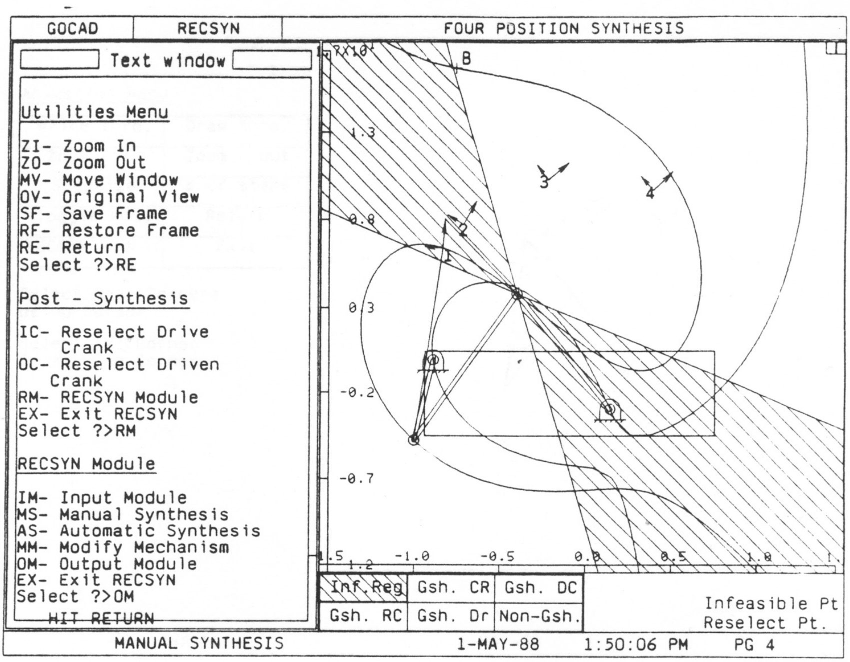

Fig. 4 A screen shot from the RECSYN program for synthesizing a motion generator for four precision positions. Both the centerpoint and circlepoint curves are shown. The user can select points from either curve. The small coordinate systems represent the four precision position definitions. The crosshatched areas represent regions that are forbidden for selecting circlepoints for the driving dyad, determined by Waldron's modified Filemon construction. They were added to the display following selection of a driven link. Point "B", labeled on the circlepoint curve, represents Ball's point, corresponding to a driving slider. Users were advised to avoid selecting circlepoints near, but not on, this point because they would tend to produce solutions with poor link length ratio, as slider solutions correspond to drivers of infinite length. As the user selected enough points to complete a linkage, its Grashof type was indicated by lighting up the appropriate box at the bottom of the screen. After the solution linkage was specified, RECSYN animated the linkage throughout its feasible range. The minimum and maximum values for the transmission angle and link lengths were also summarized. (From [27].)

parameterized and a grid of solutions mapping the entire possible solution space was constructed in a manner similar to the "TABLE" command in LINCAGES (see Fig. 3). A quality score was then assigned to each solution in the grid by applying a user-controlled objective function. The user then interactively refined the search by manually zooming in on promising portions of the grid. SOFBAL shared the multiply separated position capability of MECSYN. Unfortunately, neither MECSYN nor SOFBAL ever became widely available.

The SIXGUN program [2], authored by the group which created LINCAGES, was designed specifically for synthesizing multi-loop mechanisms[12]. The computational engine of the program could generate Burmester curves for four precision positions for either dyads or triads. Relative precision positions, described in [4], were used to implement kinematic inversion for synthesizing triads. The program would establish the topology of the mechanism being designed by reading files that were external to the program. As a result, any mechanism that could be modeled with free vectors, dyads or triads could be designed, including all the Watt and Stephenson six-bar linkages [10]. SIXGUN was never released in its most general form, since a non-expert user could potentially define a nonsensical combination of synthesis components. The LINCAGES-6 package [24] addressed that problem by modifying the original program so that it was limited to synthesizing a catalog of pre-defined six-bar linkage topologies.

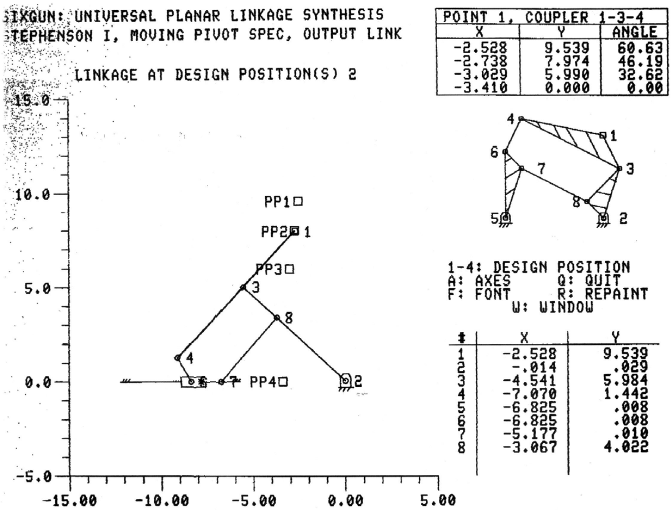

Fig. 5 A screen shot from the SIXGUN program. The program was set up to synthesize a Stephenson I six-bar linkage in this example. The generic topology of the linkage being designed was illustrated in the figure in the right column. This topology was defined by a file separate from the program itself. The numbering of the pivots indicates the order in which they were selected. In this example, the position of point 1, the angle of link 1-3-4, and the angle of link 5-6-7 were defined by precision positions input from the user. The user was then guided to select either pivot 2 or 3 from a set of Burmester curves. A free vector was then used to set the position of pivot 4 relative to pivot 1 at the first precision position. The user could then select either pivot 5 or 6 from a new set of Burmester curves generated using the placement of pivot 4. A final set of Burmester curves was generated for selecting pivots 7 and 8 by internally computing a set of relative precision positions from the earlier input and selections. Note that the solution shown utilizes a slider point; i.e., pivot 5 is at infinity.

[12] SIXGUN began as an attempt to codify the methods for synthesizing all six-bar mechanisms defined in [12], but it quickly transformed into a more generic synthesis tool.

One problem associated with designing multi-loop linkages using precision positions is that solution mechanisms are more likely to suffer circuit or branch defects than simple four-bar linkages. Mirth and Chase extended Waldron's solution rectification methods to rectify the circuit problem in Watt [20] and Stephenson [21] linkages. Watt circuit rectification was implemented in a late version of LINCAGES-6 [24]. Unfortunately, LINCAGES-6 was never migrated to computers running the WINDOWS operating system.

4 The Evolution of CAD Software for Linkage Design

The early linkage synthesis programs were typically written in FORTRAN. As the migration from minicomputers to personal computers occurred, FORTRAN became less and less used compared to C and C++. The early programs had to be rewritten to survive. During this transition, LINCAGES was maintained and enhanced, but RECSYN was not. While simplified aspects of RECSYN were reprogrammed in MATLAB for two and three positions [43], the original version of RECSYN was not reprogrammed to run on mouse driven, Windows-based platforms, and therefore the program ceased to be used.

As the personal computer became commonplace, the price of both computers and software tended to decrease significantly. In addition, both the graphics capabilities and the speed of computers increased dramatically. At the same time, equation solvers and constraint managers became more robust. This permitted the development of very sophisticated solid modeling software based on parametric design [29].

Two approaches to the development of linkage synthesis software evolved based on the increased computing and graphics capabilities available. The first utilized these capabilities directly to improve the user interface and to use search engines and knowledge bases to guide the user toward good solutions to complex design situations. Two programs which used this approach are LINCAGES and WATT [8]. LINCAGES in particular maintained the solid theoretical base discussed previously beneath a graphical user interface that guided even novice designers to good solutions to complex problems.

WATT was a suite of programs developed by Heron Technologies in the Netherlands. Not much has been published on the technical details for the WATT Suite; however, it appeared to have had a parameter reduction routine to limit the number of design parameters which must be considered. It then appeared to create a large number of trial solutions based on the most important design parameters and perform an efficient pattern-matching search of the data base to come up with viable solutions. These solutions then appeared to be refined using a genetic optimization algorithm, and a list of the best solutions were presented to the user. The user could quickly sift through the solutions by analyzing each for the full cycle of interest. The program was applicable to both path and motion synthesis, and the user could select from eight possible mechanisms[13]. The user interface was carefully designed to present the most important results on a single screen.

The WATT program was well suited to industry and was upgraded to run on Windows XP. Unfortunately, development seemed to have stopped around 2005 and the program was unavailable by 2012. Heron Technologies has removed the information for the program suite from the company web page.

During the last 10 years, solid-modeling programs such as ProEngineer, Solid-Edge, and SolidWorks have incorporated kinematic analysis capabilities which provide the designer with visually realistic linkage animations along with analytical results for velocity, acceleration, forces, mechanical advantage, and interference. The analyses can be conducted quickly, making trial and error iterations possible for relatively simple problems. In addition, the very nature of the parametric design programs gives the designer access to the constraint manager. Constraints like perpendicularity, parallelism, concentricity, coincidence, etc., are integral to the function of solid modeling programs. Because these are also some of the same geometric operations required for kinematic synthesis, solid modeling programs provide a natural environment for direct kinematic synthesis.

The SyMech Design Modules [7, 47] utilize the ProEngineer platform for the synthesis of four-bar and multi-bar mechanisms. SyMech operates within the ProEngineer environment, so the designer must already be using ProEngineer. The program uses the equations from basic kinematic theory for four-bar linkages together with mathematical optimization and an interactive graphical user interface to guide the designer toward optimum solutions. The results are displayed and analyzed by ProEngineer directly. The four-bar module (SyMech-4) incorporates the basic equations (templates) for synthesis for motion generation, path generation, crank-rocker design, and function generation. The special cases for straight-line mechanisms and parallel motion mechanisms are also included. The user can check for circuit, branch, order, and interference defects by animating the solution within the ProEngineer environment, and she can adjust the design parameters to attempt to correct for these defects.

The multi-link version of the program is called SyMech-n. Technical details on the kinematic theory for the program do not seem to have been published. However, the program appears to be suited to problems which can be solved by a series of four-bar linkages which can be connected using function generation. Again, once a basic type of linkage is identified, it can be optimized by the user by analyzing and animating the linkage in the ProEngineer environment.

Because solid modeling programs already incorporate the graphic constructions required for kinematic synthesis as preprogrammed constraints, a novel approach to synthesis has been proposed by Kinzel, Schmiedeler, and Pennock [17]. This approach does not require a separate program for kinematic synthesis because all of the operations are accomplished within the parametric design program. The kinematic constructions are set up for a generic problem in the parametric design

[13] The available mechanisms were the four-bar, slider-crank, geared five-bar, Watt 1 six-bar, Watt 2 six-bar, Stephenson 1 six-bar, Stephenson 3 six-bar, and eight-bar for parallel motion.

environment. Design parameters are adjusted to produce a solution in real time by using either the drag function on the graphics display or by typing in numerical values to force the design to conform to predefined specifications. In essence, the designer produces a "program" in the graphics environment to solve an entire class of problems simply by changing the parametric variables directly. The construction constraints are maintained by the program's constraint manager. This approach is called "graphical constraint programming" or GCP. This procedure can be used directly for crank-rocker design, function generation and motion generation. Even the 5-position problem in motion generation can be solved using this procedure. The procedure also works for path generation if the solid modeling program can store the coordinates of points along the path to be followed. Mirth [19] applied the GCP approach to the synthesis of six-bar linkages.

5 A Possible Future for CAD Programs for Linkage Synthesis

Linkages permeate the design environment, but the number of individuals who solve problems complex enough to require programs like KINSYN, LINCAGES, RECSYN, SyMech, and WATT is relatively small. The number is further reduced by the fact that modern solid modeling programs are so easy to use that even moderately complex problems can be solved iteratively in the graphics environment. The number of tractable design problems is further expanded by GCP, which does not require an extensive knowledge of kinematic theory or programming. Therefore, it is unlikely that any future company can survive if that company's only revenue stream is based on the sales of kinematic synthesis software. On the other hand, it is possible to develop and maintain sophisticated kinematic design programs within universities or in businesses which use the programs as a tool for product design or consulting. Such programs can be sold for supplementary revenue, which can justify making them available outside the home institution. Therefore, hopefully programs like LINCAGES and SyMech will survive well into the future.

In addition, it is recommended that solid modeling vendors include simple synthesis modules as part of their basic environment in much the same way that they provide analysis modules now. They should also promote using the basic environment for sophisticated designs using GCP. While a learning curve is associated with the process, it is well within the capabilities of technical school graduates or experienced designers.

6 Conclusions

The market for kinematic software is too small to expect a large number of linkage synthesis packages to be available in the future. Nevertheless, the impact of the computer assisted linkage synthesis programs that have been developed should not be underestimated. KINSYN may have constituted the first truly interactive computer aided engineering system, leveraging both the distinct computational capabilities of the machine and the intuitive capabilities of the human in the loop. LINCAGES and RECSYN extended that strategy. These groundbreaking programs may have inspired later interactive computer aided engineering applications.

The time savings of utilizing interactive linkage synthesis tools is dramatic. An optimal solution might be found in the course of an hour rather than days or even weeks. In some cases, the computer based tools were equally useful for bringing to light quickly that no practical solutions were available using a certain set of precision positions. Previously, the designer may have invested a great amount of effort to reach the same conclusion. The interactive programs can also indicate that the problem might be correctable by relaxing a constraint on the original positions.

As graphical user interfaces have improved, the scope of problems that can be solved quickly in the computer aided drafting environment has increased. Therefore, the need for standalone kinematic synthesis programs has decreased. However, a class of problems is always likely to exist that is sufficiently complex that they cannot be solved easily by manual iterative methods alone, even by experienced designers. Therefore, the development of special kinematic synthesis programs, especially in universities and research departments, continues to be justified.

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