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MEKIN2D: SUITE FOR PLANAR MECHANISM KINEMATICS

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ABSTRACT

MeKin2D is a collection of subroutines for kinematic simulation of planar linkages using a modular approach, for synthesis and analysis of disk-cam mechanisms with various types of followers, and for involute gear generation. The original set of subroutines accompanies as supplementary material a book by this same author released in 2014. These, as well as other subroutines added since the book has been released are presented in the paper, together with examples accompanied by animations.

INTRODUCTION

Currently there is a variety of computer software available for linkage and cam mechanism kinematics, either free, freeware or proprietary [2]-[25]. Most of them implement general, iterative schemes to simulate the mechanism motion, which are known however to be slow, and therefore less suitable for optimum design through repeated analysis. Mechanism synthesis software is actually not as common compared to its analysis counterpart. In turn, most cam-follower programs [5], [6], [10], [13], [14] perform cam profile synthesis for a given follower motion rather than kinematic analysis, with the exception of [2], [6] and [10] which appear to do both. In this paper the computer subroutines gathered in a suite named MeKin2D will be discussed. These have been grouped in libraries LibMec2D, LibMecIn, LibAssur and LibCams [1]. An additional library called LibPlots useful to generate graphs of various kinematic parameters of the mechanism will be also briefly introduced, as well as an AutoLisp application for involute gear generation within AutoCAD software [1].

LibMecIn can be used to define basic inputs such as cranks, sliders and RTRR oscillating slide actuators. Other active modules available are RRRR chains with a powered floating joint, RTRTR chains with two powered floating joints, and powered 6R triads and tetrads. Note that in the abbreviations for these kinematic chains an underscore "_" designates a powered joint, while R stands for a rotational joint and T stands for a translational joint.

LibAssur contains subroutines for modeling passive modules i.e. all possible dyads, as well as triads and tetrads with six rotational joints. It also includes subroutines for modeling a variety of geared and rack-and-pinion linkages.

LibMec2D provides a number of subroutines for defining offset points and for attaching complex shapes to moving links. The shapes can be either described from within the calling program, or they can be read from file. Also available from LibMec2D are subroutines for adding to simulations linear and angular measures, velocities and accelerations as vectors, and loci of moving points.

Finally, LibCams provides subroutines for the kinematic synthesis as well as analysis of disk-cams with translating and oscillating follower, flat or pointed.

Figure 1: A mechanized wooden character.

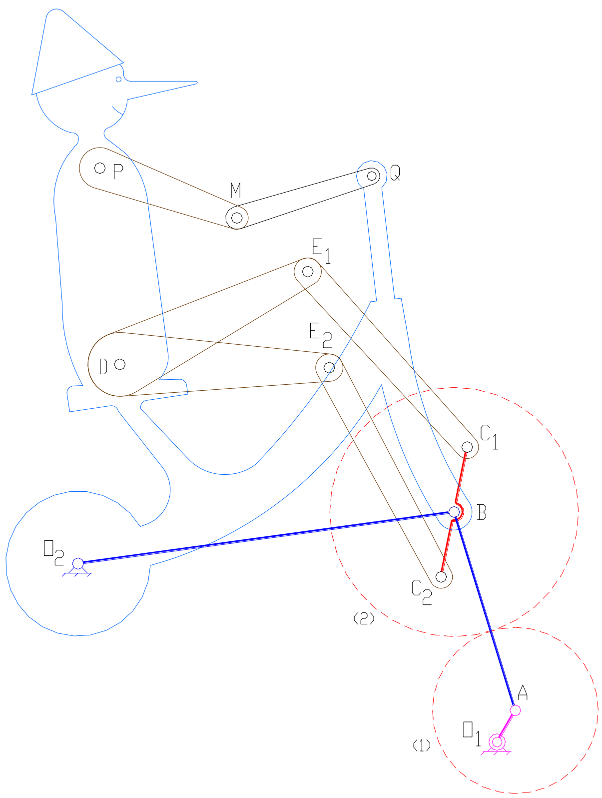

Figure 2: Simulation of the animated character in Figure 1 done using MeKin2D subroutines.

MODULAR KINEMATICS OF PLANAR MECHANISMS

Modular kinematic analysis of mechanisms uses general subroutines that can be assembled together in computationally efficient simulation programs [26]-[37]. Firstly, the input module subroutine(s) are called, followed by those associated to the modules that form the rest of the mechanism. The most commonly encountered input modules are the crank, the slider and the R<u>T</u>RR oscillating slide actuator. These are amplified with assemblies of links and joints with at least two potential joints called *neutral modules*, which added to the mechanism do not alter its overall mobility [38]-[42].

Figure 1 shows a wooden animated character [43], while Figure 2 is the simulated version of the same done using MeKin2D subroutines. The interested reader can find similar characters described in reference [44] originating from Disney Research. The mechanism in Figure 2 has been modeled as follows: Crank O_1A drives a RRR dyad to form the four-bar linkage O_1ABO_2. A gear-pair module is then used to extract the motion delivered by pinion (1) to gear (2), the latter being free to rotate about pin joint B. Points D, P and Q offset to rocker O_2B are then defined. Likewise, offset points C_1 and C_2 that move together with gear (2) are added to the simulation. These offset points serve to expand the mechanism with RRR dyads C_1E_1D, C_2E_2E and PMQ.

Note that dyad PMQ (the arm of the character) forms an immobile Baranov truss [39], and can therefore be excluded from the analysis i.e. it can be defined together with the shape attached to link O_2B. As presented however, it serves to illustrate what an Assur Group is i.e. *an assembly of links and joints which, if added to, or removed from a mechanism do not alter its mobility*. For conformity, all known dyads and the most common higher order Assur groups (triads, tetrads, pentads and hexads) [38]-[42] have been systematized in Tables A1 and A2 at the end of this paper.

The shape representing the character's upper body, together with the tricycle frame and rear wheel are read by the simulation program from an ASCII file as (*x*,*y*) pairs. These have been first drawn inside AutoCAD as polylines using Figure 1 as a template, then they were exported to DXF, and finally to a text file. The leg and arm shapes could have been read from ASCII as well. As shown however, they were automatically attached to the respective links by calling specialized LibMec2D subroutines (Figure 3). The labels and angular measures visible in Figure 3 are the result of calling other MeKin2D subroutines. Additional such examples are available throughout the paper and in Appendix.

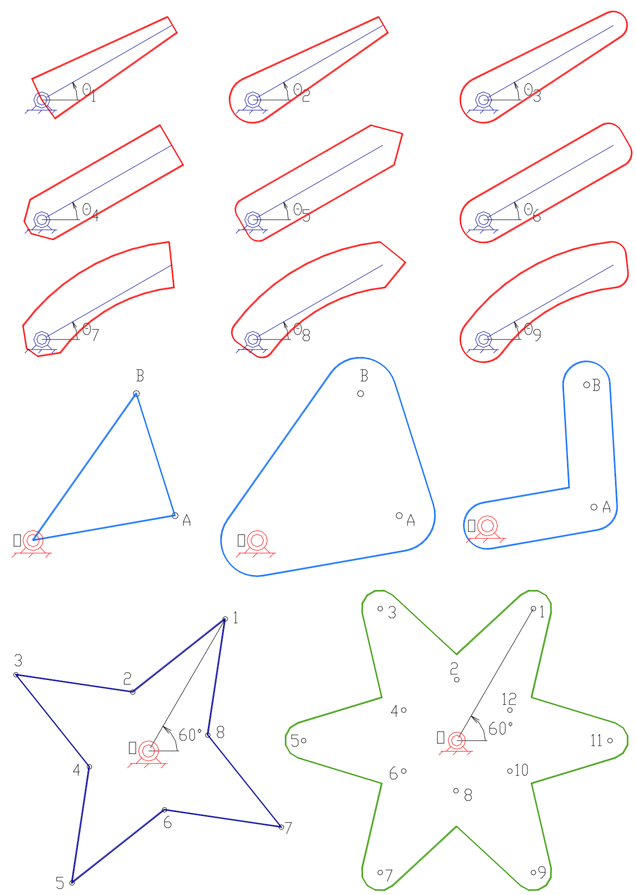

Figure 3: Binary, ternary and polynary shapes generated using LibMec2D subroutines.

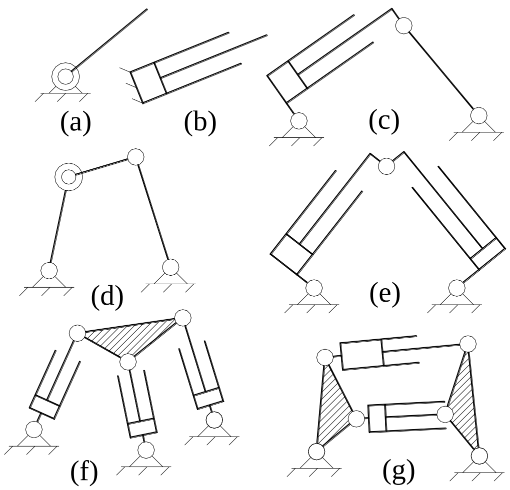

Figure 4: Powered modules available from MeKin2D.

INPUT KINEMATIC MODULE

Figure 4 lists the powered modules currently available from the LibMecIn library. Of these, the cranks, the slider and the RTRR oscillating-slide actuator (Figures 4-a, b and c) are the most commonly used in practice. Also available are a four-bar with a driven coupler RRRR (Figure 4-d), RTRTR powered chains (Figure 4-e), powered triads with one, two or three linear motors (Figure 4-f), and powered tetrads with one or two linear motors (Figure 4-g). Note that powered modules (c) to (g) can be attached to (distinct) moving links, not just to the ground.

An example of a mechanism driven by sliders is given in Figure 5-a [45]. A second bi-mobile leg mechanism formed using a centric RTRTR chain is shown in Figure 5-b [46]. Both are actuated by linear motors programed to generate periodic motions that have been established interactively. The foot locus and timing marker spacing were simultaneously observed while conducting these manual searches.

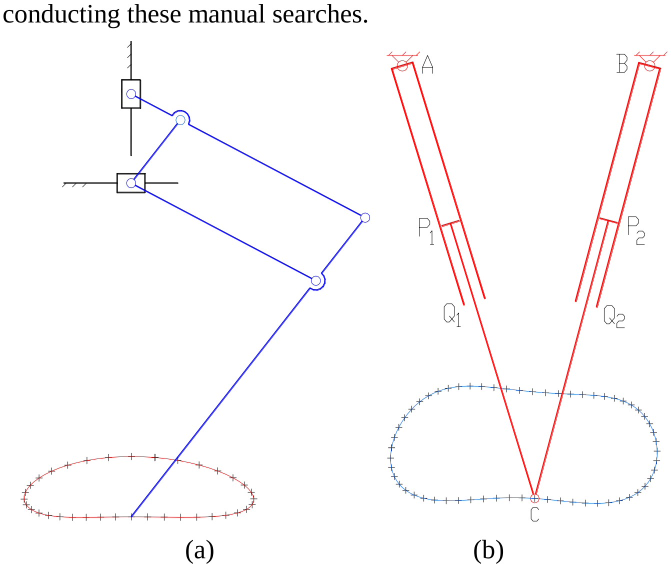

Figure 5: Simulations of bi-mobile leg mechanisms.

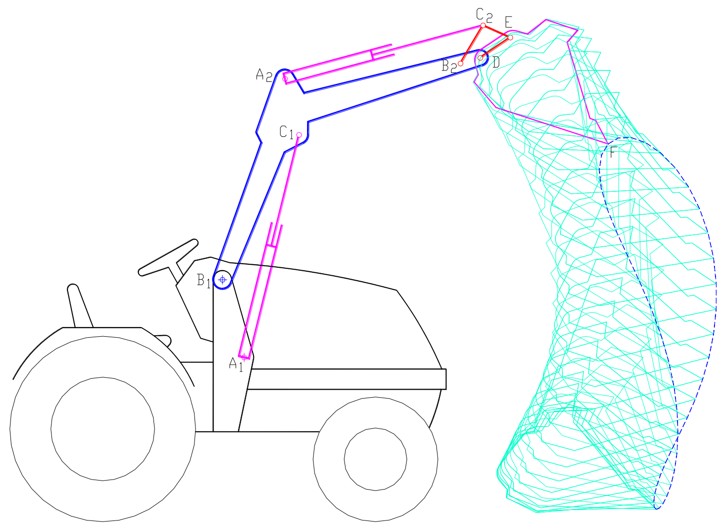

Figure 6: Front loader mechanism that uses two RTRR oscillating slide actuators and one RRR dyad.

Figure 6 is the result of simulating a front loader mechanism driven by two RTRR oscillating slide actuators. The accumulated contours of the bucket and locus of the bucket tip are shown overlapped in this figure. Same as in Figure 2, the tractor body, loader boom and bucket have been drawn inside AutoCAD, and the vertices of the respective polylines have then been exported to ASCII files as (x,y) pairs.

An everyday life example of RRRR powered module use can be found in oscillating fans [45]. Figure 7 shows a simulation that includes such a RRRR powered module, driven from the ground by two cranks. The locus of offset point P attached to link BC is also show, accompanied by the velocity (v), and the normal (a_n) and tangential (a_t) acceleration vectors of P, both produced by calling LibMec2D subroutines.

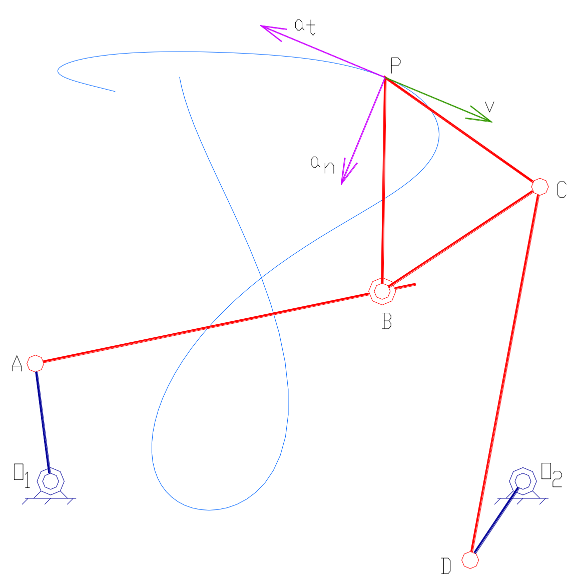

Figure 7: Simulation of a RRRR powered module driven by two cranks.

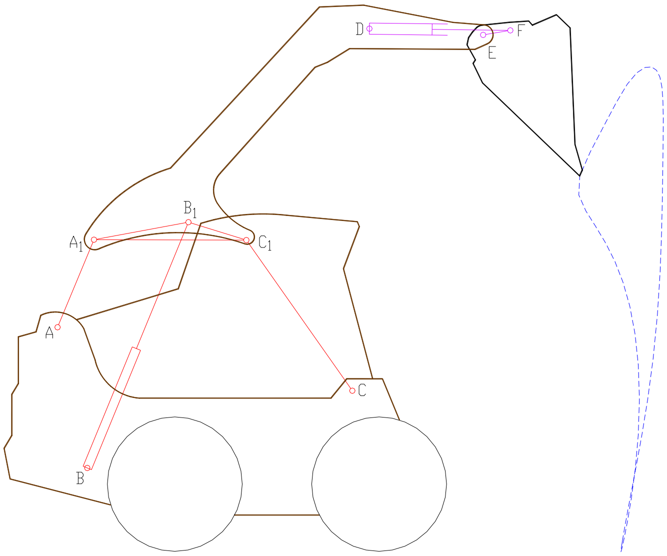

Figure 8: Simulation of the mechanism of a skid loader that includes a powered triad and a RTRR actuator.

The simulations in Figures 8 and 9 are examples of powered 6R triad use. The skid loader mechanism in Figure 8 employs a triad having one of its binary links converted into a linear motor. A RTRR module is additionally used to actuate the loader bucket. In turn, Figure 9 is a direct kinematics simulation of a redundant 6 DOF planar parallel manipulator consisting of a triple powered 6R triad that is actuated from the ground by cranks O_1A, O_1B and O_1C.

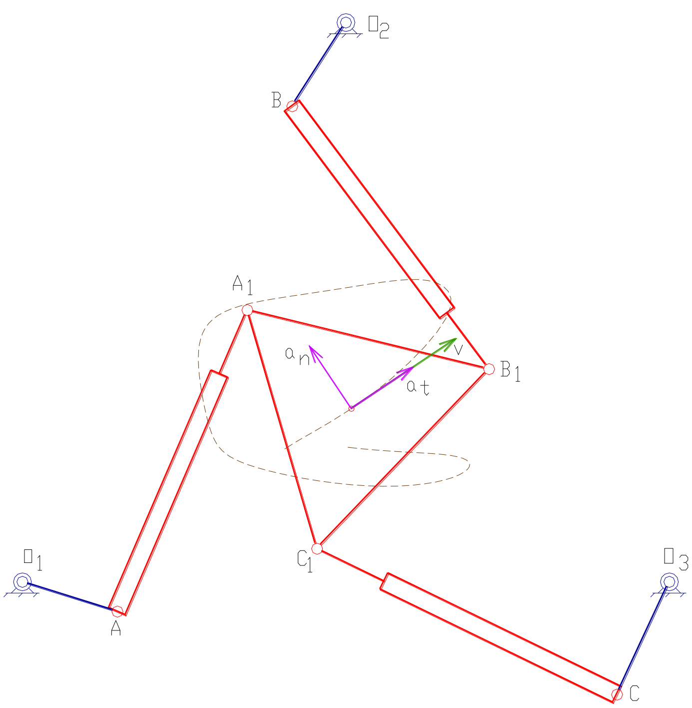

Figure 9: Direct kinematic simulation of a redundant planar parallel manipulator.

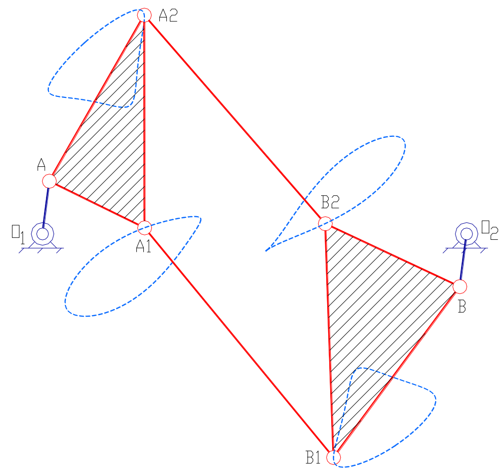

Figure 10: Simulation of a mechanism with a 6R tetrad that is driven from the ground by two cranks.

PASIVE MODULE

LibAssur provides subroutines for modeling the kinematics of the most commonly encountered *passive modules*, also known as *neutral modules*. These include all isomers of the RRR, RRT, RTR and RTT dyads (see Table A1 in Appendix), the 6R triad, and the 6R tetrad (see Table A2 in Appendix). More details on the concept of *dyadic isomers* can be found [1] and [41].

Examples of mechanisms with dyads are available in Figures 2 and 6 and in the Appendix. The powered triad in Figures 4-f and the powered tetrad in Figures 4-g can be straightforwardly converted into passive modules by holding their linear actuators at constant length. An example of a mechanism with a tetrad is shown in Figure 10.

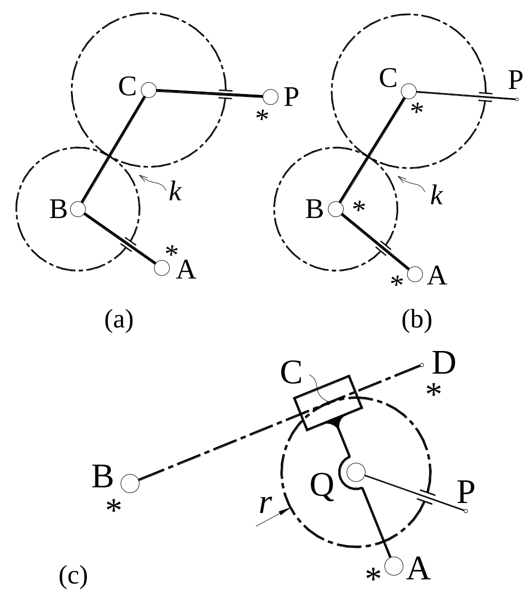

Figure 11: Geared modules available as LibAsur subroutines.

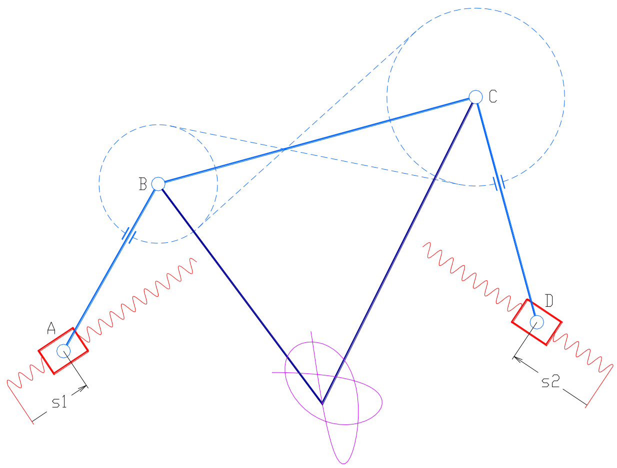

Figure 12: A geared RRR dyad driven from the ground via two powered screws, also showing the locus of a point on link BC.

GEARED LINKAGE MODULES

MeKin2D suite implements so far three geared-linkage passive modules as shown in Figure 11, where an asterisk indicates a potential connection. The module in Figure 11-a will be called a *geared dyad*, the module in Figure 11-b will be called a *rotary-motion extractor*, while Figure 11-c shows a *translational motion extractor*. The transmission ratio $\boldsymbol{k}$ between the two gears, and the radius $\boldsymbol{r}$ of the pinion must be specified as inputs. An option exists to represent the gear pairs as friction wheels, or as a cross-belt-sprocket pair (Figure 12). Involute gears generated separately can be attached as shapes. For a positive transmission ratio $\boldsymbol{k}$, a timing belt transmission can be shown instead of friction wheels (Figure 13).

The reader has probably noticed that the animated character in Figure 2 employs a rotary motion extractor represented as a friction-wheel pair, and also noticed that the example in Figure 12 is reminiscent of the upper loop portion of a scissor jack of the type disclosed in patent [47].

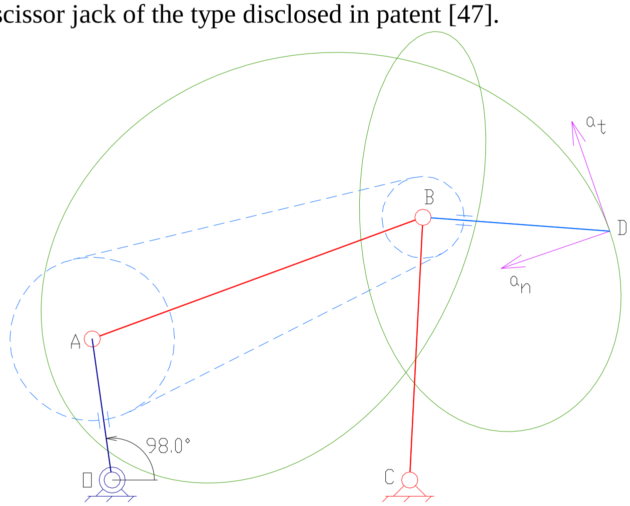

Figure 13: Geared module with $\boldsymbol{k} > 0$ extracting the motion between the crank and the coupler of a four-bar linkage.

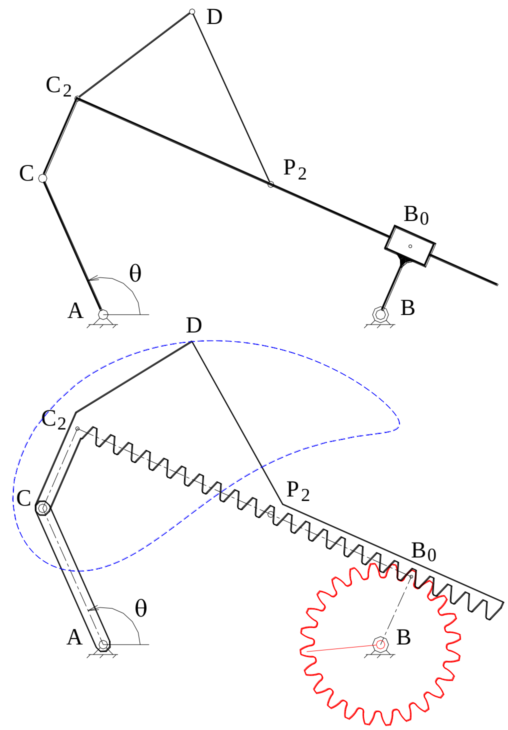

Figure 14: A geared four-bar linkage modeled using a RTR dyad and a rack-and-pinion motion extractor.

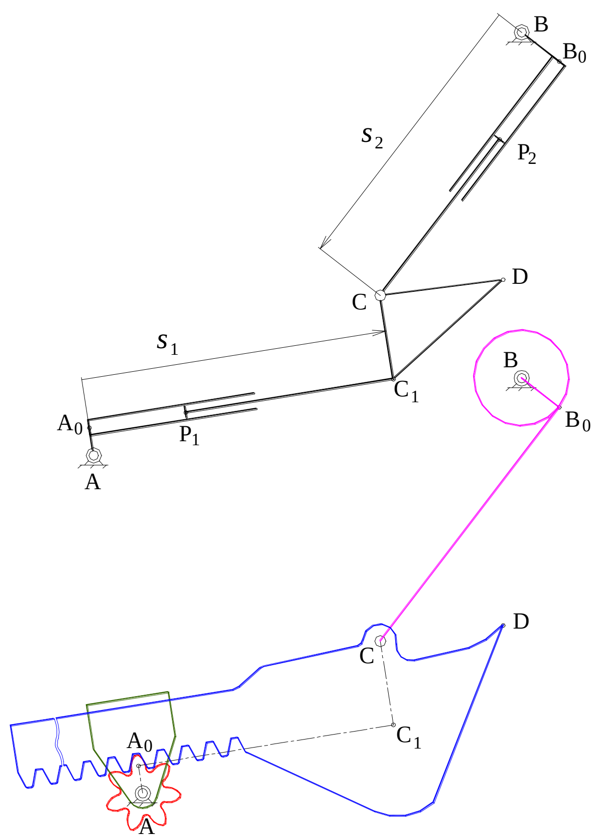

Figure 15: A rope shovel mechanism modeled using a RTRTR powered module and two rack-and-pinion motion extractors.

Examples of rack-and-pinion motion extractor use are available in Figures 14 and 15 (see also the Appendix). Note that such motion extractors can be also embodied as a cable-spool pairs (see Figure 15).

It is relevant to mention that the kinematics of the geared dyad in Figure 11-a can be solved only iteratively, while the motion extractors in Figures 11-b and c are solvable analytically. Regarding the involute gear profiles occurring in some figures throughout the paper, these have been generated inside AutoCAD using an AutoLisp application named Gears.LSP and available with [1].

SYNTHESIS THROUGH REPEATED ANALYSIS

Linkage mechanism design is vast subject with very many publications available to the interested reader. Other than graphical methods (which should be performed inside a CAD package for added accuracy), synthesis of linkages can be either of exact-point type, or optimization based. Trial-and-error designs through repeated analyses, frequently performed in practice, are nothing but manually conducted optimizations. If a computer can be instructed on how to select a batter solution, than the task of link-length and joint-location adjustment can be done automatically.

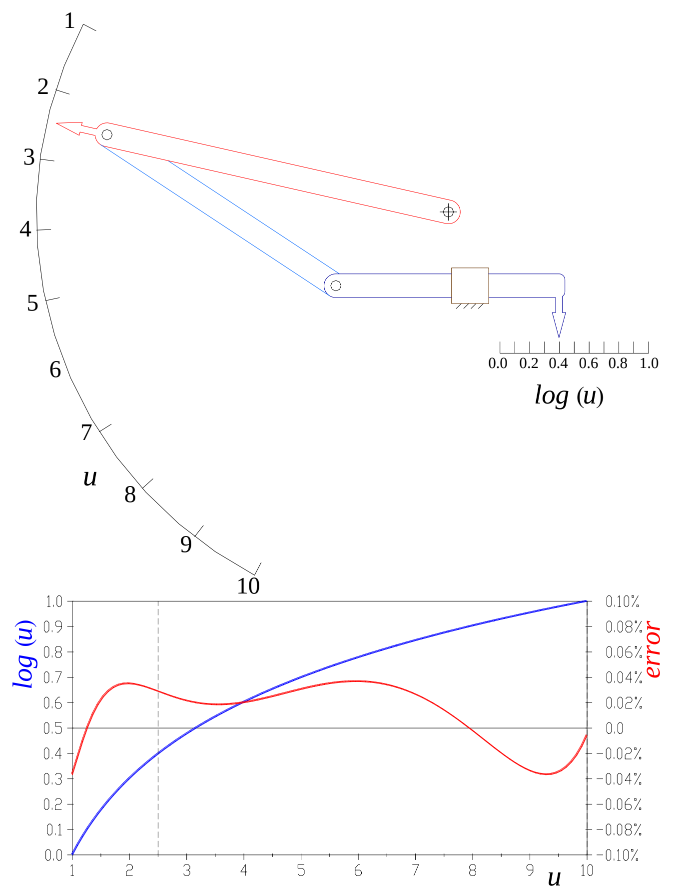

Figure 16: Rocker-slider function generating mechanism.

Known synthesis problems can be for: (a) the generation of function, (b) for cyclic input-output correlation (i.e. for specified dwell motions, time ratios or velocity ratios), (c) for path and (d) motion generation – both without or with timing. All these could be performed by additionally imposing good motion transmission characteristics or minimum and maximum link-length proportions [48]. Optimum synthesis can be done on a modified mechanism, or through repeated analysis on the actual mechanism.

An example of an optimally design mechanism is shown in Figure 16, which is a slider-rocker linkage that approximates the function *log*(*u*) for $1 < u < 10$ at less than 0.04% error.

CAM MECHANISM EXAMPLES

LibCams is a collection of subroutines for disk cam profile synthesis and for cam-follower mechanism analysis. The type of followers allowed are translational or rotational, either pointed, with roller, or curvilinear (concave or convex). In a synthesis problem follower motion must be supplied to the respective LibCams subroutine as a table of displacement values (linear or angular) vs. cam angle. The cam is then generated as follower envelope in a motion inversion process.

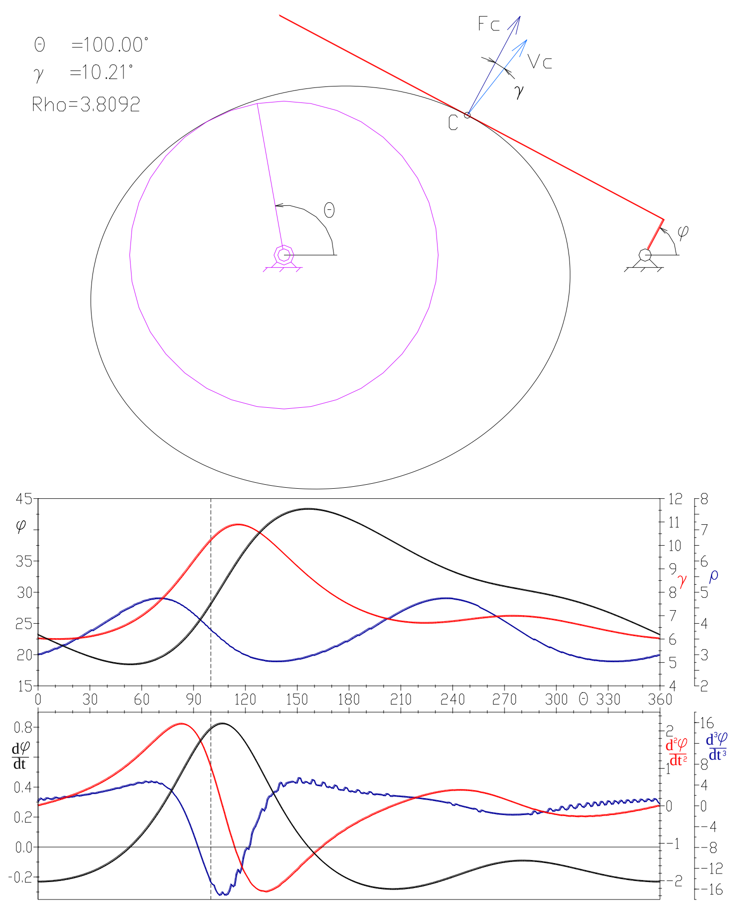

Figure 17: Analysis of a cam follower pair performed using LibCams subroutines.

To perform a kinematic analysis, the follower type must be specified, together with the cam profile as a collection of (x,y) points. Results will be follower displacement, pressure angle γ, and radius of curvature ρ at the contact point, all as functions of the cam angle θ. Figure 17 shows the analysis of an eccentric elliptic cam with oscillating flat follower. The companion velocity, acceleration and jerk diagrams have been all obtained through numerical differentiation of the $\varphi(\theta)$ data.

CONCLUSIONS

The main features of the MeKin2D suite for kinematic simulation of planar linkages and for the synthesis and analysis of disk-cam mechanisms have been presented accompanied by animations. The examples shown in the Appendix include repetitive mechanisms, mechanism from robotics and material handling. All the figures in this paper are available as animation files from [49], with additional examples being available from website [50].

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APPENDIX

Table A1: All possible dyadic isomers (column I), simplified embodiments (column II) and applications (column III).

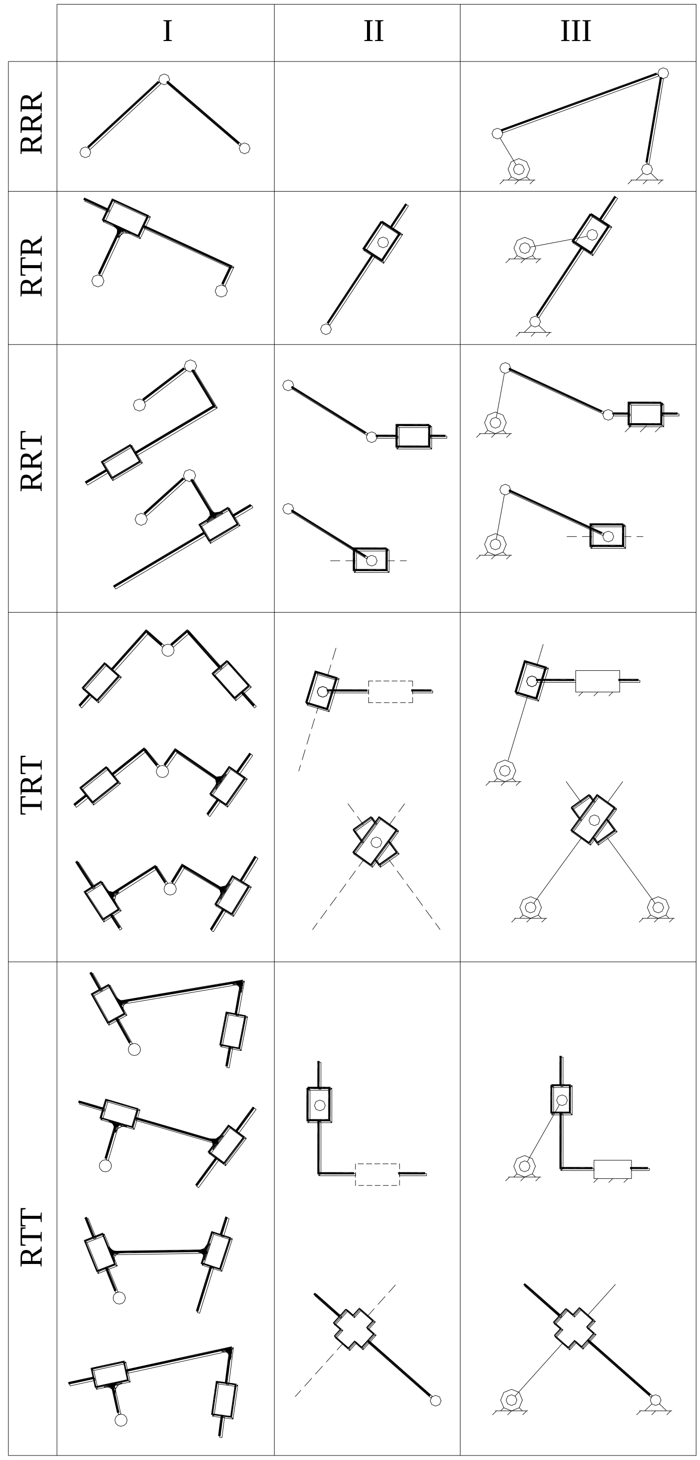
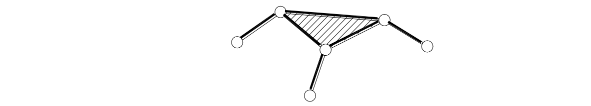
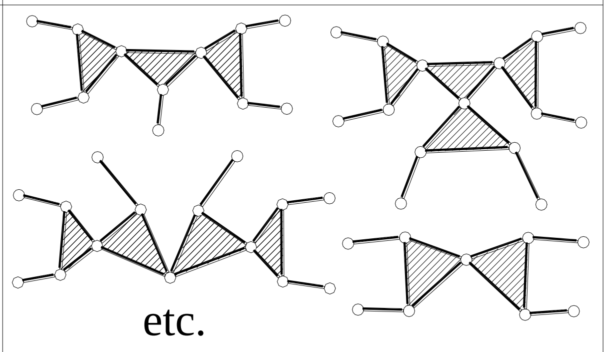
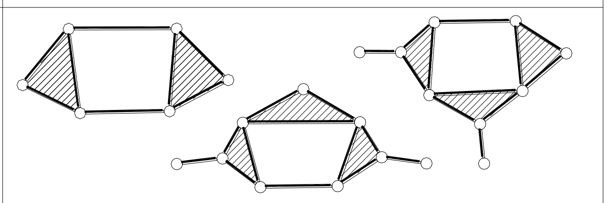
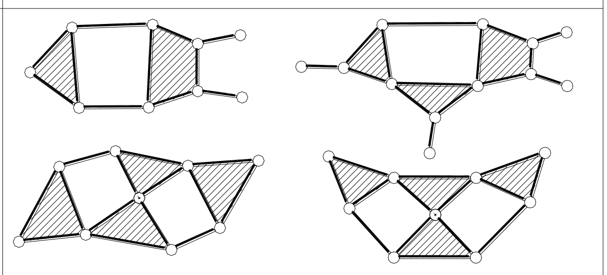
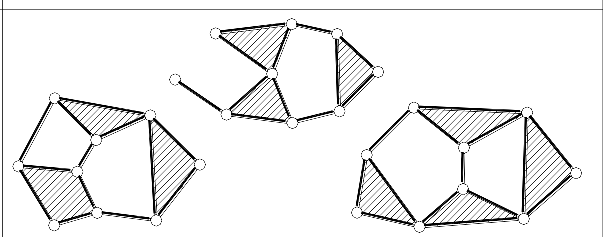
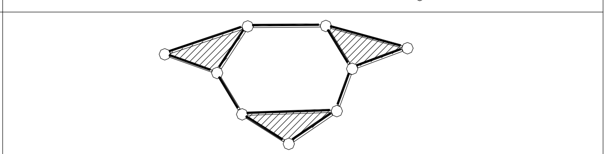


Table A2: The most common higher order Assur groups.

Triad	
Multiple Triad	
Tetrad	
Multiple Tetrad	
Pentad	
Hexad	

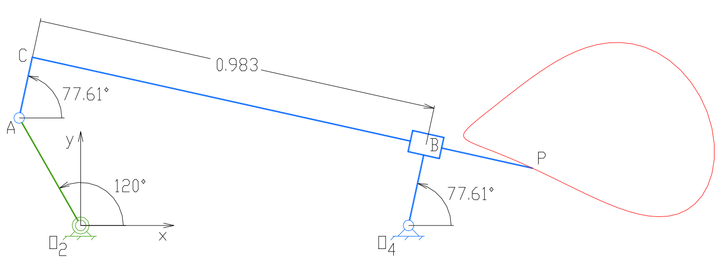


Figure A1: Crank driven RTR dyad with meters and locus of P.

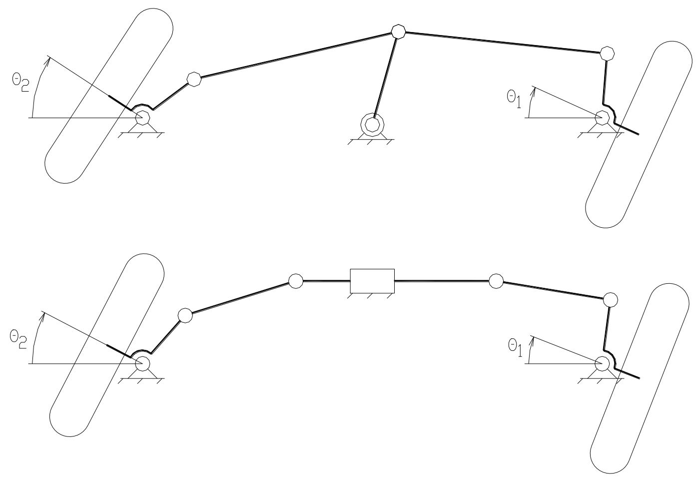


Figure A2: Bell crank and rack-and-pinion steering mechanisms.

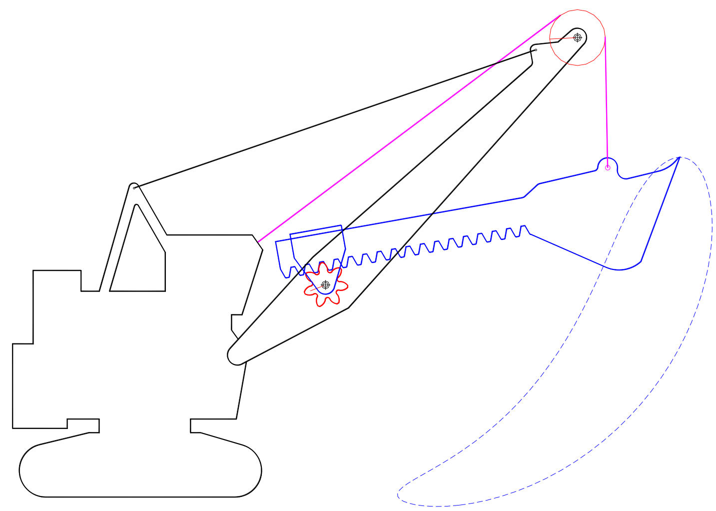


Figure A3: Rope shovel [1].

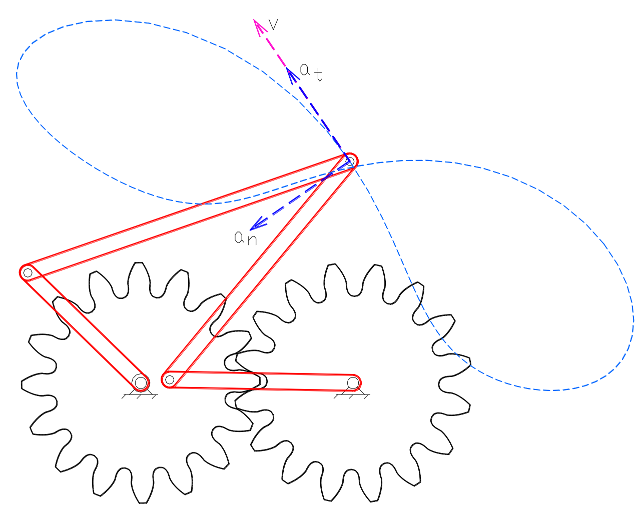


Figure A4: A geared-five bar linkage.

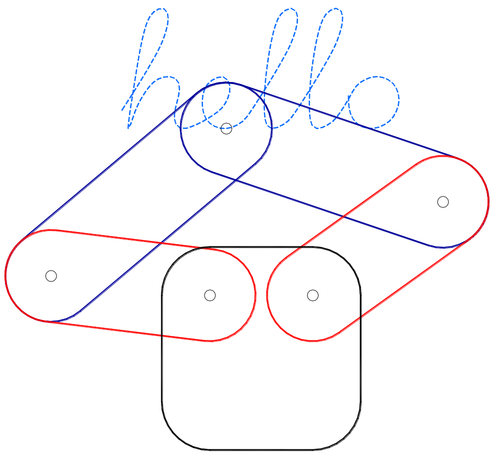


Figure A5: Direct kinematics of a 5R robot [46].

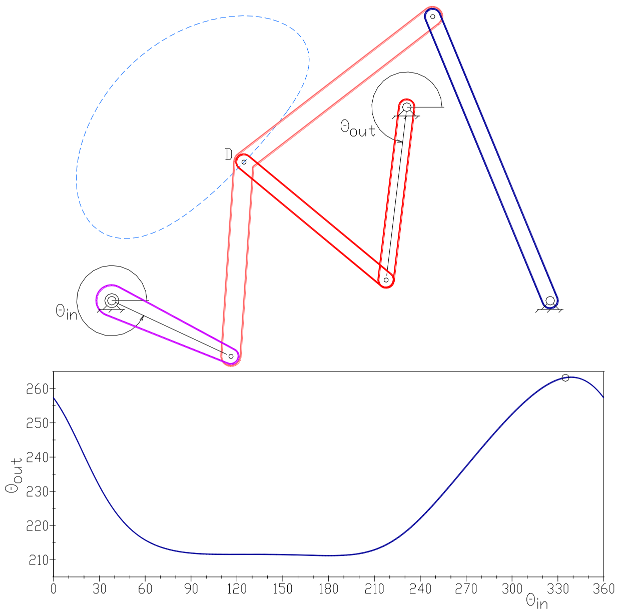


Figure A6: A dwell six-bar linkage and I/O comet plot [1].

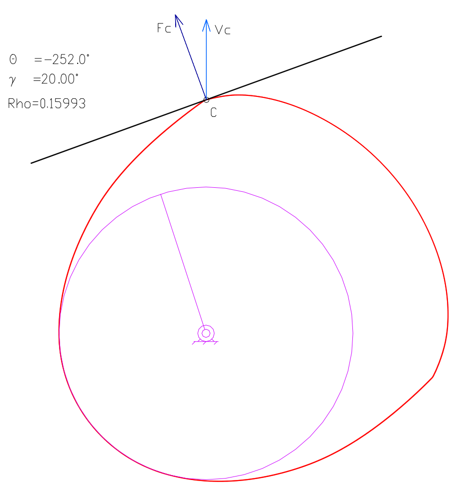


Figure A7: Analysis of a cam mechanism with flat translating follower [1].

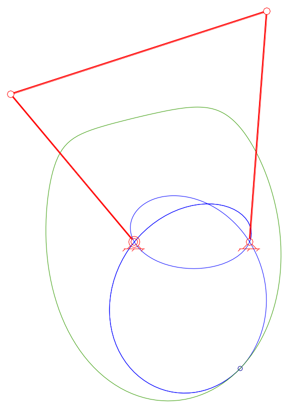


Figure A8: Fixed and moving centrodes of a four-bar linkage.

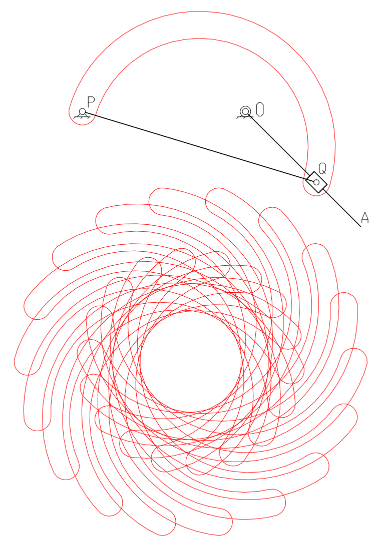


Figure A9: Simulation of a repetitive mechanism [1].

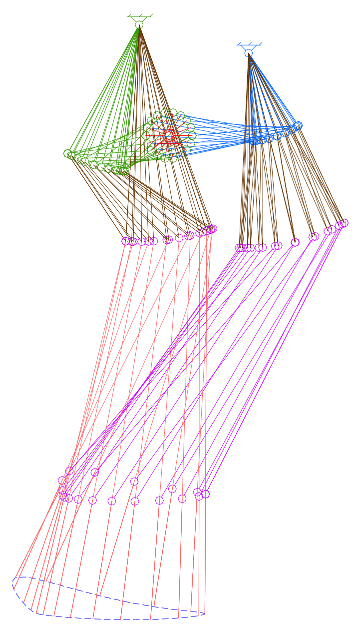


Figure A10: Simulation of a leg mechanism shown as accumulated positions [46].