MechAnalyzer: 3D Model Based Mechanism Learning Software

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Abstract: *Study of various planar and spatial linkages is a first step towards the learning of Multi body dynamics. It is covered in Mechanism Design or Theory of Machines, which is a basic course taught in the curriculum of Mechanical Engineering. Students learn to formulate and solve kinematic and dynamic equations to analyze different types of mechanisms. A computer-based approach to solve these equations becomes imminent when the number of equations increases and also for a quick and better understanding through visualization. Currently, there are several free and commercially available software which can help students in this matter. Unfortunately, considerable amount of time is required to train students in order to use them. In this paper, a software named "MechAnalyzer" is presented, which is developed to analyze and simulate the mechanisms that are already preloaded in it, hence, reducing the time and effort required to get started with it.*

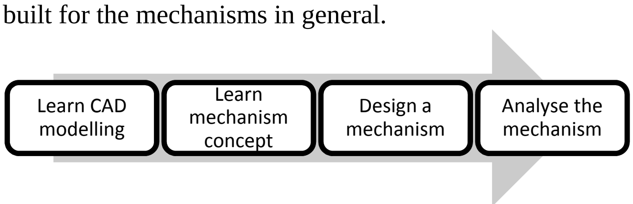
Keywords: Simulation, Educational software, Four-bar, Slider crank, Five-bar linkage, Forward kinematics

I. Introduction

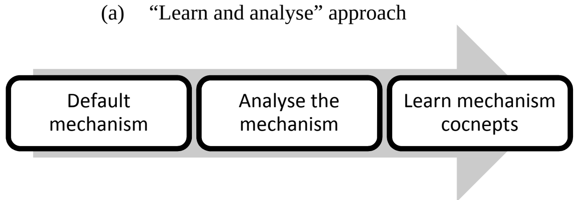
Prior to 1950, the graphical methods were extensively employed for the design of planar mechanisms and to perform their kinematic analysis. But, the study was limited only to simple mechanisms due to the lack of strong numerical design methods. After 1950, development of several theories and advent of computers have enabled solutions for more sophisticated problems and also offered better visualisation techniques. As the usage of mechanisms has increased in industries and research, mechanisms have been a part of engineering curriculum of various institutions all over the world.

The concepts in Theory of Machines is best learnt when a student can view the animation of a mechanism's motion. Traditional methods of building the linkage model is time consuming and tiresome. This has led to an increased interest in the use of simulation software for the teaching and learning of the subject. In the recent years, many mechanism visualisation tools have been developed to help teachers teach and students learn in an effective way.

Use of several commercial software packages like Universal Mechanisms [1], SAM [2], Ch Mechanisms Toolkit [3], etc. might appear as the best option at the outset. Though, they are powerful, reliable and are loaded with several features, a student has to spend considerable amount of time in learning to use these commercial packages. Also, many engineering colleges do not have such expensive proprietary software available in their labs. Hence, students cannot easily use them. Besides, the aspect of modelling the mechanisms takes away significant amount of time and energy of a student. Most importantly, a student has to learn the concepts of mechanisms to analyse its kinematics. This approach is referred here as "Learn and analyse" approach as shown in Fig. 1(a). Instead, if a student can skip the modelling part by choosing from the preloaded mechanism and perform its analyses, the student can visualise and learn the concepts in a more effective way. This is referred here as "Learn while analysing" and it is illustrated in Fig. 1(b). In other words, a software with an inbuilt template of four-bar mechanism loaded with its associated features (like inversions, straight line linkages, complete analyses) essential for the conceptual understanding of the four-bar mechanism is much better compared to a software which is built for the mechanisms in general.



(a) "Learn and analyse" approach



(b) "Learn while analyzing" approach

Fig. 1. Approches to learn mechanism concepts

Consequently, many universities across the world followed the "Learn while analysing" approach and developed educational computer tools to help the students understand mechanism concepts. Authors of some textbooks [4-6] have included a CD-ROM with a simulation program to complement the book contents. A brief overview of software developed to analyze mechanisms is given in Table 1. The mechanisms software are evaluated based on the development platform, available analysis such as Forward Kinematics (FKin) and Inverse Dynamics (IDyn), availability to download and use, provision to plot graph for the analysis results and if a set of preloaded mechanisms are present, which can be readily simulated. The features of the software like animation, graph plots and availability of preloaded mechanism would be beneficial to the student community for effective learning, all of which is not present in any of the software listed in Table 1, that are currently available.

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Software	**Platform**	**FKin**	**IDyn**	**Availability**	**Graph plot**	**Preloaded mechanisms**	**Other details**
MMTool [7]	Developed for MS DOS with graphics	Yes	No	No	No	No	User can sketch a generic mechanism. Synthesis of links and workspace detection is also possible
LINCAGES 2000 [8]	Developed for Windows NT	Yes	NA	No	No	Yes	A tool for synthesis for four bar and six bar mechanisms only
GIM [9]	Desktop application using C#, OpenGL	Yes	No	Yes	Yes	No	Synthesis and Analysis of spatial mechanisms
Linkage 2.0 [10]	Desktop application using C++	Yes	No	Yes	No	No	
LinkSim [11]	Desktop application	Yes	No	Yes	No	No	Basic level software with very limited controls
SOLVE [12]	Online tool. Runs on Flash in a Web Browser	Yes	Yes	Yes	No	Yes	Needs constant internet connection for operation

Table 1: Comparison of mechanism simulation software

Considering some of the gaps found in the software reviewed above, a new software named MechAnalyzer has been developed by the authors and is reported in this paper. The software is developed with a focus on analyses of planar mechanisms, which can be extended to spatial mechanisms in the future. At present, the current version, Version 2, can perform kinematic analysis of four-bar, slider crank and five-bar linkage mechanisms. The results of the analyses can be viewed in the form of animation and graph plots.

In the remainder of the paper, an overview and the features of MechAnalyzer software is presented in Section II. Section III has the formulations of kinematic analyses used in the software. In Section IV, the results obtained in MechAnalyzer were validated with those obtained using a commercial software named RecurDyn [13] and found to be matching. The future work planned to be done is discussed in Section V, followed by the conclusions.

II. Overview of MechAnalyzer

MechAnalyzer software is developed as a Microsoft desktop application using Visual C# and OpenTK, a .NET wrapper for OpenGL. The following features were considered for its development:

a) It should follow “Learn while analysing” approach, thus saving students’ effort required to build a model for analysis. This makes the study of mechanisms more fun and attractive for students
b) It should be easy to use
c) It should be able to animate and plot interactive graph of analyses results
d) It should be less dependent on other software and should be easily distributed to the end users
e) It should cover all the concepts associated with a mechanism like inversions, branching, coupler-curve trace, forward kinematics, inverse dynamics, etc.
f) It should be able to export analyses results for further analyses and validation purposes.

A. Workflow

In its present implementation, MechAnalyzer can analyse forward kinematics of some basic mechanisms like four-bar, slider-crank and five-bar mechanisms. The illustration of its workflow is given in Fig. 2. MechAnalyzer requires the length of the links of the selected mechanism as the input and inversion (if applicable) to perform forward kinematic analysis. The results of the analyses can be viewed as animation of the selected mechanism and as graph plots.

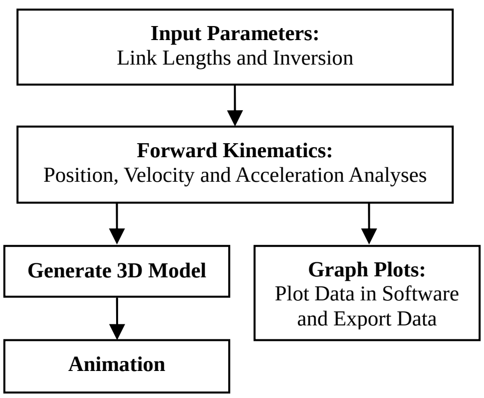


Fig. 2. Workflow of MechAnalyzer

B. Forward kinematics

Based on the input parameters entered by the student using the buttons/controls in MechAnalyzer user interface, forward kinematics of the selected mechanism is performed. It comprises of position, velocity and acceleration analyses of each link of the mechanism. The formulations for position analysis are based on geometric approach, whereas for velocity and acceleration, numerical differentiation is performed. These are covered separately in Section III.

C. Generation of 3D model and animation

Based on the position analysis results and the length of input links, the shapes of the links are generated in OpenTK/OpenGL for the rendering of the mechanism in MechAnalyzer. During the position analysis, the minimum and maximum angle of the input joint(s) are also determined so that the limits for the animation can be set. Between the limits, the animation of the mechanism can be seen where the 3D model of the mechanism moves from its initial position to final position. The mechanism's motion is shown in a loop. The user interface of MechAnalyzer software for five-bar mechanism is shown in Fig. 3.

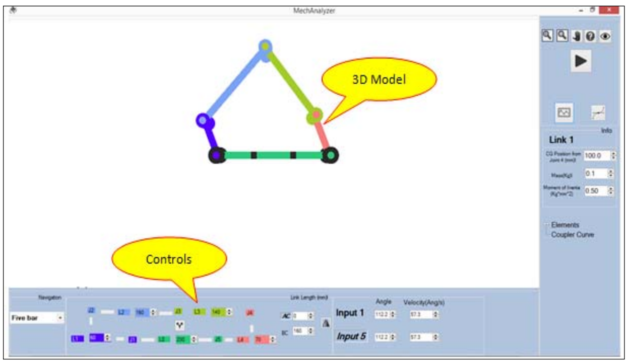


Fig. 3. 3D Model of a mechanism

MechAnalyzer also has capabilities for pan, zoom and tilt using which the 3D model of a mechanism can be viewed from various angles. Simulation parameters like speed of the animation, angular velocity of the motor can be set and the results can be viewed in the form of animation of all the links and the trace of the coupler point. The coupler curves can be traced for different link lengths with different colours for the sake of visual comparison, as illustrated in Fig. 4. The trace of the coupler point can also be drawn during animation to see the path it follows.

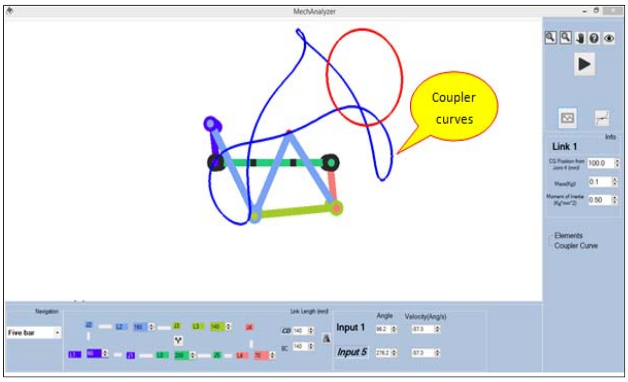


Fig. 4. Traces of coupler curves

D. Graph plots

An open-source C# plot library named ZedGraph has been integrated with MechAnalyzer to plot the graphs of the analyses results. The graph in MechAnalyzer is made interactive so that the student can get simultaneous visualisation of the motion of the 3D model and the plots. Whenever the mouse cursor is hovered over the graph plot, the corresponding state of the mechanism is displayed side by side, as illustrated in Fig. 5. This helps the student to relate the mechanism to its position, velocity, and acceleration at any position of the input link.

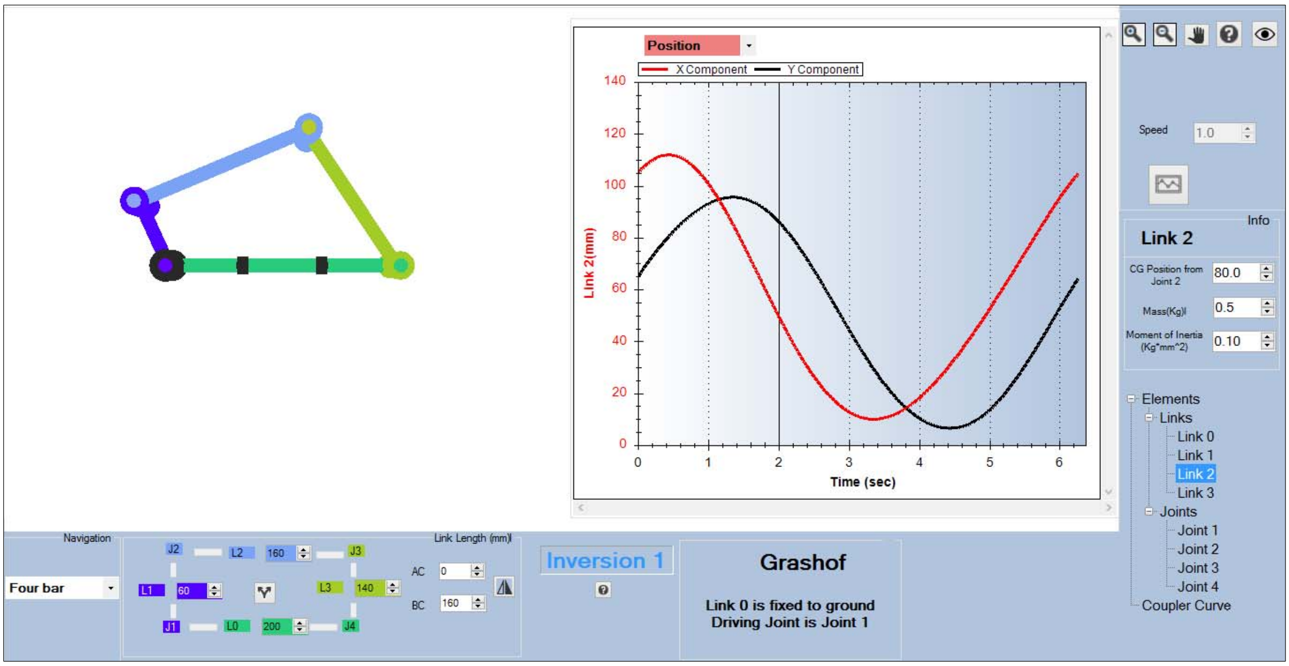
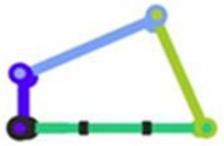


Fig. 5. Graph displaying components of position analysis of Link 2 of a four-bar mechanism

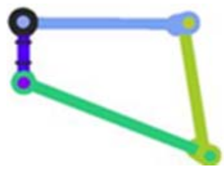
For further analyses or for validating the results with other software, the graph plots can be saved as an image and the data can also be exported as a CSV (comma separated values) that can be opened in any spread sheet application, e.g., in MS-Excel.

E. Inversions and configurations

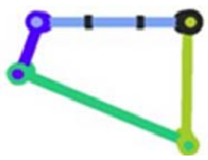
One of the challenging topics while teaching and learning four-bar and slider-crank mechanisms is the concept of inversions. MechAnalyzer has a functionality of changing the inversions on the fly and the forward kinematics data. The model gets updated instantaneously. A student can switch between different inversions by fixing different links, visualized by straps on the fixed link, and observe the animation, as illustrated in Fig. 6. For a five-bar mechanism simulation, the motors can be switched to different joints, such that the motors are not necessarily on the joints on either ends of the fixed link.



(a) First Inversion



(b) Second Inversion

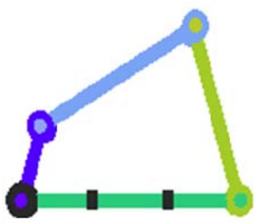


(c) Third Inversion

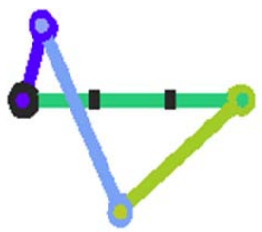
(d) Fourth Inversion

Fig. 6. Inversions of a four-bar mechanism

In addition, four-bar mechanism has multiple solutions for a given input crank angle. MechAnalyzer determines both possible solutions and lets a student swap between the two solutions, also referred as configurations or branches. An example of two possible solutions for a particular input crank angle is shown in Fig. 7. This helps in better understanding of the multiple solutions of a four-bar mechanism.



(a) Configuration 1

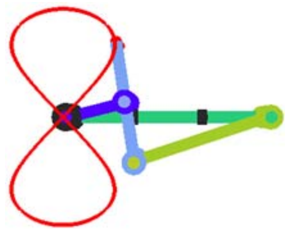


(b) Configuration 2

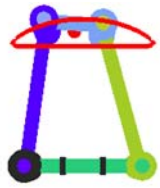
Fig. 7. Two solutions of a four-bar mechanism

F. Special mechanisms

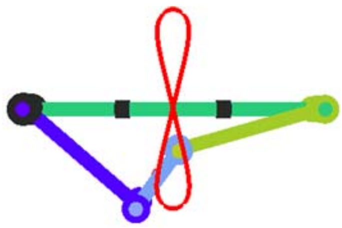
Several examples exist where a straight line motion in a machine is required to perform some operation. During the design of such a machine, certain mechanisms are designed to provide a straight line motion. Some approximate straight line generating mechanisms are also possible by setting particular length for the links of a four-bar mechanism. Some of these are available in MechAnalyzer software, where students can select a mechanism and see the animation to observe a straight line during a range of its full motion. These mechanisms are shown in Fig. 8.



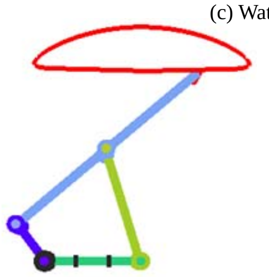
(a) Evans Mechanism



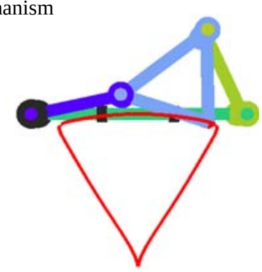
(b) Chebyshevs Mechanism



(c) Watts Mechanism



(d) Hoekens Mechanism



(e) Roberts Mechanism

Fig. 8. Special four-bar mechanisms

III. Kinematic Analysis

Kinematic analysis of a mechanism deals with the study of the position, velocity and acceleration of its joints and links, without considering the forces acting on it or the resultant forces due to the motion. In any motion simulation software, the position analysis is done first to perform the animation of the motion of the mechanism at hand. Then, the velocity and acceleration analyses are performed which are typically shown as graph plots. MechAnalyzer also follows similar approach and the formulations used are explained next.

A. Position analysis

For the position analysis of a mechanism, the length of its links and the position (angle or translation) of the input joint(s) are needed as input. In MechAnalyzer, geometric approaches were used to determine the positions of the ends of all the links of the mechanism. Accordingly, the joint angles or translations of all the joints, except the input joints were determined. The formulation used for the mechanisms are explained next.

A1. Four-bar mechanism

The nomenclature used for the four-bar mechanism is shown in Fig. 9. Four-bar mechanism has one degree-of-freedom (DOF) and it requires only one joint input to define the system. Link0 is fixed to the ground and the driving joint is considered as Joint1. The length of Link0 is considered as L_0, length of Link1 as L_1 and so on. For simplification purpose, Joint1 is assumed to be at the origin.

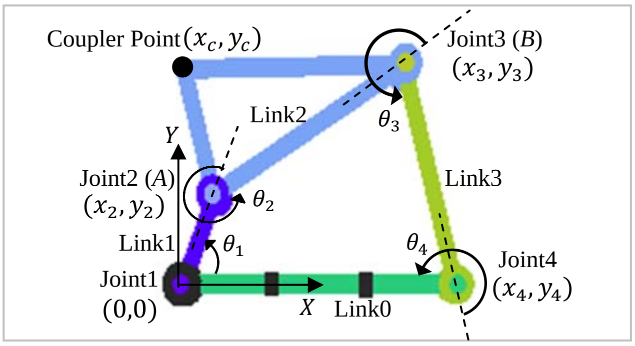


Fig. 9. Nomenclature of four-bar mechanism

The coordinates of Joint2 (*A*) are found from

$$x_2 = L_1 \cos\theta_1 \quad (1)$$

$$y_2 = L_1 \sin\theta_1 \quad (2)$$

The coordinates of Joint3 (*B*) are then determined using the equations of circles about Joint2 (x_2,y_2) and Joint4 (x_4, y_4)

$$L_2{}^2 = (x_3 - x_2)^2 + (y_3 - y_2)^2 \quad (3)$$

$$L_3{}^2 = (x_3 - L_0)^2 + y_3{}^2 \quad (4)$$

Equations (3) and (4) provide a pair of simultaneous equations in x_3 and y_3, i.e., the coordinates of point *B*. Subtracting (4) from (3) gives an expression for x_3 as

$$x_3 = \frac{L_1{}^2 - L_2{}^2 + L_3{}^2 - L_0{}^2}{2(x_2 - L_0)} - \frac{2y_2y_3}{2(x_2 - L_0)} \quad (5)$$

Substitute the known component of Equation (5) as *S*, i.e.,

$$S = \frac{L_1{}^2 - L_2{}^2 + L_3{}^2 - L_0{}^2}{2(x_2 - L_0)} \quad (6)$$

The expression of x_3 is then reduces to

$$x_3 = S - \frac{2y_2y_3}{2(x_2 - L_0)} \quad (7)$$

Substituting (7) into (4) results in a quadratic equation in y_3 yielding its solution as

$$y_3 = \frac{-Q \pm \sqrt{Q^2 - 4PR}}{2P} \quad (8)$$

where *P*, *Q* and *R* are given by,

$$P = \frac{y_2{}^2}{(x_2 - L_0)^2} + 1 \quad (9)$$

$$Q = \frac{2y_2(L_0 - S)}{(x_2 - L_0)} \quad (10)$$

$$R = (L_0 - S)^2 - L_3{}^2 \quad (11)$$

Note that the expression for y_3 has two possible solutions, which correspond to the two configurations or branches of a four-bar mechanism as explained in Section II/E. Depending on the configuration chosen, the value of y_3 is determined using (8) and then the value of x_3 is found using (7). Knowing the coordinates of Joint2 and Joint3, i.e., points *A* and *B*, the joint angles of Joint2, Joint3 and Joint4 are determined using simple trigonometric principles. For different inversions, the fixed link and the input joint are changed as per the inversion, and position analysis is repeated.

The above set of calculations is also repeated for different values of θ_1 and the corresponding values of the coordinates of the position of joints are obtained, to perform animation of the mechanism for a range of input motion.

A2. Slider crank mechanism

For a slider crank mechanism, the nomenclature used to represent the links and joints is illustrated in Fig. 10. It also has a single DOF. Link0 is fixed to ground and Joint1 is considered as the input joint. Remaining conventions are same as in the four-bar mechanism.

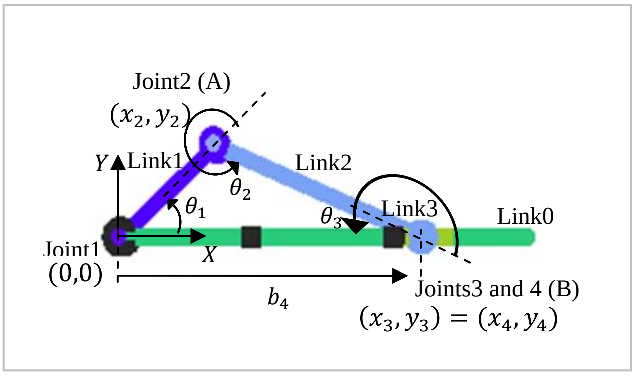


Fig. 10. Nomenclature of slider-crank mechanism

The coordinates of Joint2 (*A*) are determined as

$$x_2 = L_1 \cos\theta_1 \quad (12)$$

$$y_2 = L_1 \sin\theta_1 \quad (13)$$

The coordinates of Joint3 (*B*) are found using the equations of circle about Joint2 (*A*), i.e.,

$$L_2{}^2 = (x_3 - x_2)^2 + (y_3 - y_2)^2 \quad (14)$$

Joint1 is assumed to be at origin and the slider is assumed to move along *X* axis. Hence, the value of y_3 is

$$y_3 = 0 \quad (15)$$

Substituting (15) in (14), the value of x_3 is determined as

$$x_3 = x_2 \pm \sqrt{L_2{}^2 - (y_2)^2} \quad (16)$$

With points *A* and *B* known, the joint angles and translational distance are determined using trigonometric principles.

A3. Five-bar mechanism

Five-bar mechanism has 2 DOFs, i.e., it needs two joint inputs to define its motion. The nomenclature used to define a five-bar mechanism is shown in Fig. 11. Link0 is fixed to ground and Joint1 and Joint5 are considered as input joints.

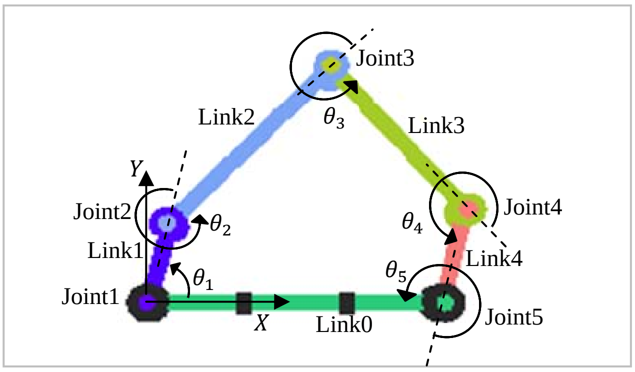


Fig. 11. Nomenclature of a five-bar mechanism

To perform position analysis of a five-bar mechanism, it is reduced to an appropriate four-bar mechanism. This is achieved by replacing Link0 and Link4 by an imaginary link, Link04, as shown in Fig. 12 by dotted line. The length of Link04, i.e.,L_{04} is calculated using Cosine rule as

$$L_{04} = \sqrt{L_0{}^2 + \ L_4{}^2 - 2L_0L_4\cos\theta_5'} \tag{17}$$

where,

$$\theta_5' = \theta_5 - 180° \tag{18}$$

The angle θ_{04} that imaginary link Link04 makes with Link0 is determined using Sine rule as

$$\theta_{04} = \sin^{-1}\left[\frac{L_4\sin\theta_5''}{L_{04}}\right] \tag{19}$$

where,

$$\theta_5'' = 360° - \theta_5 \tag{20}$$

Referring to Fig. 12, the equivalent four-bar mechanism now comprises of Link04, Link1, Link2 and Link3. Joint1 is considered as the input joint and the input angle is considered as

$$\theta_1' = \ \theta_1 - \theta_{04} \tag{21}$$

With the equivalent four-bar mechanism, the position analysis can be performed as explained in Section III/A/A1.

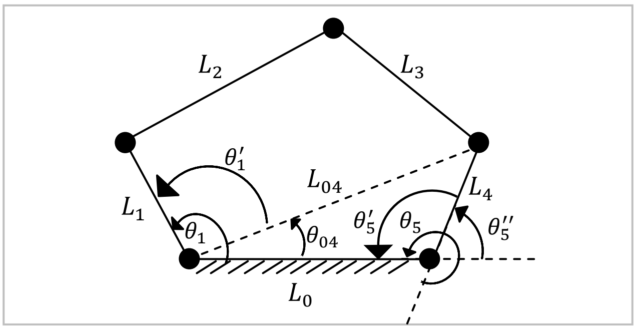


Fig. 12. Equivalent four-bar mechanism

B. Velocity analysis

For the velocity analysis, numerical method was used in MechAnalyzer, as opposed to an analytical method. This was done to get the velocity of any point on the links. The velocity of a joint can also be obtained. If the positions of any link or joint are P_1 and P_2 at time t_1 and t_2, then the velocity at time t_2, i.e., V_2, is determined as

$$V_2 = \frac{P_2 - P_1}{t_2 - t_1} \tag{22}$$

The time interval (t_2-t_1) is kept constant throughout the simulation. So, equation (22) becomes

$$V_2 = \frac{P_2 - P_1}{t} \tag{23}$$

where,

$$t = t_2 - t_1 \tag{24}$$

The time interval t is chosen to be small enough to give accurate results for all configurations.

C. Acceleration analysis

The approach to calculate the angular acceleration of joints or acceleration of any point on links is similar to the calculation methodology discussed in the previous section on velocity analysis. If V_1 and V_2 are the velocities at time t_1 and t_2, then the acceleration at time t_2, i.e., A_2, is given by

$$A_2 = \frac{V_2 - V_1}{t} \tag{25}$$

IV. Validation of Results

The results obtained from MechAnalyzer were compared with those obtained using RecurDyn, a multibody simulation software, for the same input parameters. For this, all the three mechanisms in MechAnalyzer were individually modelled in RecurDyn and motion simulation was performed on them. The results from MechAnalyzer and RecurDyn were separately exported and plotted in MATLAB environment.

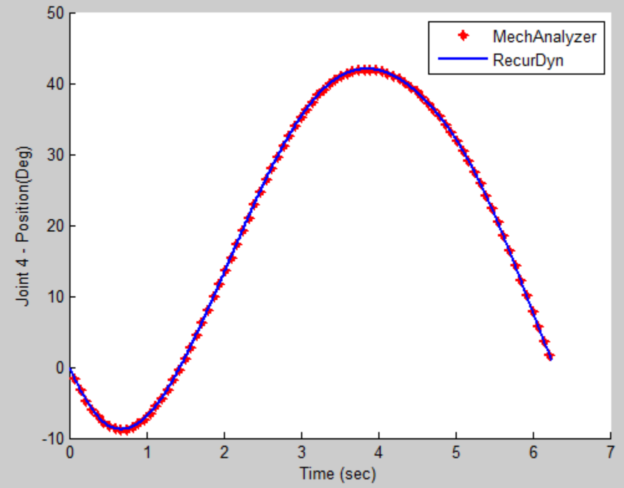
For demonstration purposes, the kinematic analysis, i.e., position, velocity and acceleration analyses, performed for a four-bar mechanism in MechAnalyzer and RecurDyn are reported here. The input data considered for the comparison is given in Table 2.

Link Name	Link Length
Link0	200 mm
Link1	60 mm
Link2	160 mm
Link3	140 mm

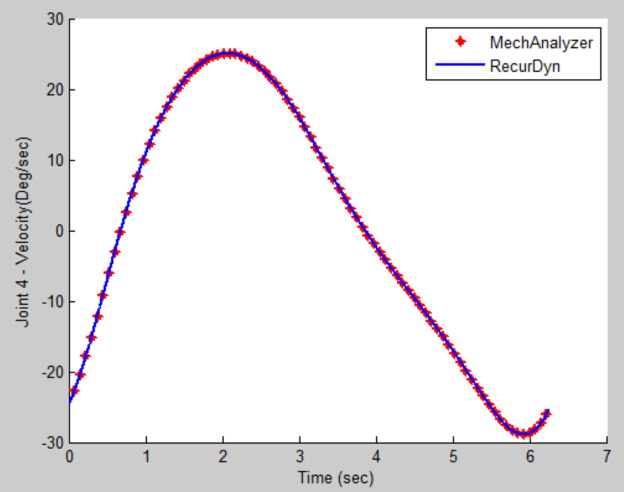
Table 2: Input parameters for four-bar mechanism

The results of the analyses for all the joints and positions were compared and found to be matching, with a very little difference. For the sake of brevity, the results of only Joint 4 are given in Fig. 13.

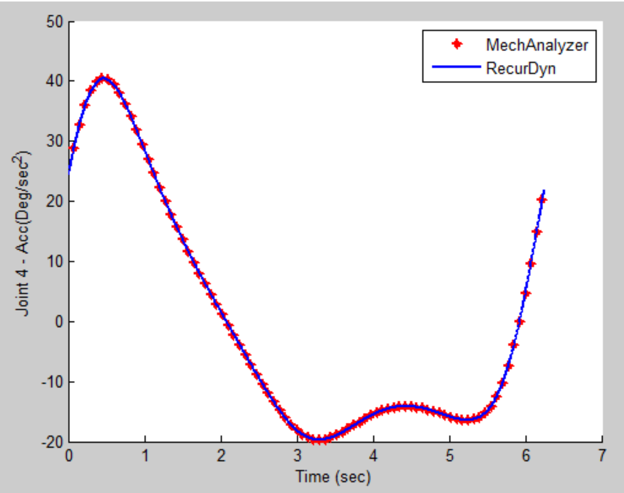
The matching results assure that MechAnalyzer can be used for educational purposes and also as a validation tool for programs developed by the students and researchers.



(a) Position analysis



(b) Velocity analysis



(c) Acceleration analysis

Fig. 13. Kinematic analysis of Joint 4 of a four-bar mechanism

V. Future Scope

MechAnalyzer software has a lot of good features, which require further fine tuning and also addition of new features. Inverse dynamics for a four-bar mechanism is already implemented in the current version, but has not been reported here. After inclusion of dynamics for other mechanisms, it will be communicated later. Some of the new features planned for implementation are:

a) Addition of basic planar mechanisms.
b) Optimisation
c) Import 3D CAD model into the software
d) Analysis of spatial mechanisms
e) Dynamic analysis
f) Spatial mechanisms
g) Interfacing with MATLAB and other software

VI. Conclusions

A new 3D-model based mechanism learning software is presented in this paper. It takes the length of links as inputs to model and perform kinematic analysis of simple mechanisms like four-bar, slider-crank and five-bar mechanisms. A student using this software can learn mechanism concepts through “Learn while analysing” approach, thus bypassing the need to build the model of the linkage in commercial software. Complete analyses can be performed for all the inversions and configurations. Animation of the mechanism’s motion and interactive graph plots can be visualized in MechAnalyzer. The current version, Version 2 of MechAnalyzer, can be downloaded and used for free from http://www.roboanalyzer.com/mechanalyzer.html.

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