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Spreadsheet-based interactive design and analysis of mechanisms using Excel and Ch

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ABSTRACT

A spreadsheet-based mechanism analysis and animation system is presented in this article. The system is developed in Excel using Ch, an embeddable C/C++ interpreter, and Ch Mechanism Toolkit. It allows users to develop and solve complicated planar mechanism problems conveniently using an easy to use Excel spreadsheets as the front end. Users can input the required data to define a mechanism in an Excel spreadsheet and execute script files associated with the work cells. The spreadsheet based system can be used for kinematic and dynamic analysis, graphical plotting, and animation for four bar, crank-slider, five bar, and six bar linkages. The system is open architecture. Users can extend the system for design and analysis of other mechanisms. Examples are provided to illustrate its ease of use. The source code for examples are available for downloading from the internet.

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1. Introduction

General purpose software packages such as Automated Dynamic Analysis of Mechanical Systems (ADAMS), Dynamic Analysis and Design System (DADS), Working Model [1] were developed to solve complicated engineering design and analysis problems. Although these software programs are powerful, learning curves for these packages are quite steep because users are assumed to have full knowledge of the subject. Special purpose software packages such as the Linkage INteractive Computer Analysis and Graphical Enhanced Synthesis Package (LINCAGES) [2,3], WATT by Heron [4], and Simulation and Analysis of Mechanisms (SAM) by Artas [5] are available for the synthesis and analysis of planar mechanisms. The software package SYNTHETICA [6] can be used for synthesis of spatial mechanisms. Compared with general purpose software packages, these specialized packages are easier to use for mechanism design and analysis.

Spreadsheet was originally created to help accountants to solve their accounting problems. Due to its friendly user interface and easy of use, it has been extensively used in many different fields. It is also widely used as an educational tool in engineering. For example, Excel spreadsheet has been used in simulating engineering systems, such as logic networks, control systems and antenna array design [7]. Spreadsheet has also been used in the field of machine design [8], such as design of worm gear geometry [9], determination of spur gear form factors [10], aircraft structure analysis [11].

To customize spreadsheets for solving complicated engineering problems, Excel spreadsheet is typically programmed in Visual Basic. Excel can also be extended by means of C code or other languages that support either OLE automation or Windows dynamic link libraries (DLL) [12]. An add-in can be created from a program making it a seamless part of the Excel Interface and can also add customized functions to automate complex processes.

Ch [13–16] is a C/C++ interpreter. It conforms to the ISO C standard with extensions and contains salient features of MATLAB for numerical computing, graphical plotting, and script computing. The Ch Mechanism Toolkit [17,18] developed in Ch is significantly different from other software packages. The users are able to examine the available source code and demo programs provided within the toolkit to solve practical engineering problems. Open source programs based on Ch and Mechanism Toolkit for kinematic synthesis of mechanisms are also available [19]. Based on the Ch Mechanism Toolkit, a Web-based mechanism design and analysis module has been developed [20,21]. The user can design and analyze mechanisms interactively through a Web browser without computer programming. The Web-based system provides the user with a convenient means to quickly obtain solution to many mechanism design problems. It is especially suitable for teaching and learning mechanism design and analysis. The Ch Mechanism Toolkit has been used as a teaching tool in an undergraduate course "Computer-Aided Mechanism Design" at the University of California, Davis [22]. Students can use the toolkit's high-level building





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blocks to develop their own software programs for solving complicated engineering analysis and design problems. For example students were assigned to develop a complete program for analysis and animation of a Whitworth quick return mechanism [23]. It allows the user to verify their solutions quickly with numerical and graphical output as well as animation. The toolkit provides students with the opportunity to study and understand the algorithms and their software implementation for mechanism design and analysis.

Although Web-based mechanism design and analysis is easy to use, it typically needs network connection. To take advantage of the power of Excel spreadsheet and Ch Mechanism Toolkit, we have developed a software package for spreadsheet-based interactive mechanism design and analysis [24]. In this software package, Excel spreadsheet is used as the front end for friendly user interface, numerical computations in the back end are performed in Ch Mechanism Toolkit through ChExcel [25]. ChExcel is an Excel add-in that integrates Microsoft Excel's spreadsheet interface with Ch's computational power. ChExcel allows users to access the computation power of Ch from Excel worksheets and Visual Basic for Applications (VBA). ChExcel lets user to communicate and exchange data between the Ch and Excel workspace. The communication between Excel and Ch is controlled by a few simple function, keeping the interface simple and easy to use.

The spreadsheet-based interactive mechanism design and analysis package contains spreadsheets and C/C++ script files for various planar mechanisms including four bar, five bar, and multiloop six bar linkages. The system is open architecture. Users can extend the system to solve other complicated planar mechanism problems conveniently using an easy to use Excel spreadsheets as the user interface. Users can input the required data to define a mechanism in an Excel spreadsheet and execute C/C++ script files associated with the work cells. The software package is ideal for rapid prototyping and teaching.

In this paper, design, implementation and application of spreadsheet-based interactive mechanism analysis and animation are described. The presentation of this paper will focus primarily on four bar linkages. However, the ideas and concepts are applicable to other mechanisms as well.

2. Features of spreadsheet-based mechanism analysis and animation

The spreadsheet-based mechanism design and analysis system incorporates all features available in the Ch Mechanism Toolkit through spreadsheets, users can solve complicated mechanism problems without programming. Some tedious and often complicated processes, such as kinematic and dynamic analysis of a four bar linkage, can be performed with ease. A user only needs to enter parameters and execute ChExcel functions in appropriate cells in a spreadsheet.

An Excel sheet for mechanism analysis is typically separated into two sections, namely input and output sections. The input section gets the required data, which are then processed in the back end using the Ch computational engine. The result is displayed in appropriate cells in the output section of the same Excel sheet. Excel sheets were developed for design and analysis of commonly used mechanisms, such as animation of a four bar mechanism and plotting of a coupler curve. They can be downloaded from the internet [24]. The first section of a spreadsheet is typically for the input data that are required for the analysis such as the link lengths, phase angles, velocity and acceleration of the driving link. Different options can be selected for handling different situations such as solving for output angles for a given input angle or plotting for a coupler curve. The Excel sheets are also available for dealing with the four bar linkage synthesis and dynamic analysis. Excel sheets can also be developed for special four bar linkages such as Grashof, non-Grashof, straight line, quick return and symmetrical linkages as well as singular configurations.

Aside from a four bar linkage shown in Fig. 1, the software package contains Excel sheets for analysis of crank-slider, geared five bar and various six bar linkages. The available six bar linkage include the four bar slider, Stephenson I and III, as well as Watt I and II six bar linkages. Operations such as kinematic and dynamic analysis are performed on the planar linkages using C/C++ scripts in the back end that are accessed from the Excel sheet. For example, given a linkage configuration, the angular position, velocity and acceleration of various links can be determined. The Excel sheet also has the ability to invoke the graphical and animation capabilities of the Ch Mechanism Toolkit. This animation feature allows the user to visually study the behavior of the mechanism as it rotates through its entire range of motion.

3. Interface with Excel spreadsheet for mechanism analysis and animation

The Excel sheets were designed to be simple and easy to use. ChExcel functions placed in certain cells can be evaluated on accessing those cells. These functions can execute C/C++ script files using the data from the spreadsheet. An adjacent cell contains the same value with an additional symbol <=to indicate a comment cell. For example, the comment <==ChPutMatrix(C4, ''rl") in cell F4 in Fig. 2 indicates that E4 contains the ChExcel function ChPutMatrix(C4, ''rl"). When this ChExcel function is executed, the value in the cell C4 would be stored in a variable named rl in the Ch space, which is equivalent to declaring a double variable rl and initializing it with the value 12 in cell C4 as in the following C statement.

double rl = 12;

This variable rl can also be accessed from the Ch space. To execute a ChExcel function in a cell, press function key F2. The script file ''fb_pos_initialization.ch" listed in Program 1 placed in the cell E2 is first executed. File ''fb_pos_initialization.ch" must be placed in a directory specified by the system variable _path which can be specified in the system startup file, such as C: \ Program Files\SoftIntegration\embedch\config\chrc by default, or the individual startup file _chrc in the user's home

Fig. 1. A four bar linkage mechanism.

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6	R3		12				tMatrix(C6,'			
7	R4		7				tMatrix(C7,			
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9										
10	Known An	gle in Deg	gree							-
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Fig. 2. A spreadsheet for four bar linkage position analysis.

directory for Embedded Ch in ChExcel [25]. Program 1 includes the required header files and initializes the variables that would be used in the analysis. For example,

CFourbarfourbar;

in Program 1 declares an object fourbar for the class CFourbar which will be used in accessing the member function of this class from other script files. Similarly, plot is an object declared for the class CPlot to handle the plotting feature available in Ch. The variables inputlimitmin, inputlimitmax, outputlimitmin and outputlimitmax were used in processing the limits of the four bar linkage. The array's theta_ldeg and theta_2deg are the variables that store the possible two branches of solutions generated for a given input value θ_2 of the driving link 2 of a four bar linkage. Variables fourbartype and index variable i are used in an other application script which will be described later. Fig. 2 is a snap shot of the Excel sheet used in calculating the angles θ_3 and θ_4 at a given value for θ_2 . The data given are lengths r_i 's for each link, the phase angle θ_1 , and β and r_p for a coupler point shown in Fig. 1. The software module for calculating the angles θ_3 and θ_4 can be found in the Mechanism Toolkit. The zeros in column E shown in Figs. 2 and 3 indicate the successful execution of the Ch add-in functions from Excel.

Program 1. The script for initialization of variables used in position analysis of four bar linkage (fb_pos_initialization.ch)

```
#include <math.h>
#include <fourbar.h>
#include <fourbar.h>
#include <coplot.h>
#include <stdio.h>
double inputlimitmin[2], inputlimitmax[2],
    outputlimitmin[2],outputlimitmax[2];
    double theta_ldeg[1:4], theta_2deg[1:4];
    int fourbartype;
    int i;
    CFourbar fourbar;
    class CPlot plot;
```

Angular positions of the links are calculated in cell E20 in Fig. 2 using the script file fb_angularPos.ch listed in Program 2. The variables rl, r2, r3, r4, thetal, beta angleno, angle are declared and initialized with values using ChExcel function ChPutMatrix() in Fig. 2. The program first converts the input angles from degrees to radians, then determines the angular positions of links 3 and 4 using the member function CFourbar::angularPos() in the Ch Mechanism Toolkit. The function parameter for an angle for these member functions has to be in radian. Therefore, the input data in degree needs to be converted to radian. For example, statement

thetal = thetal * $M_PI/180$;

converts the tal from degree to radian. Similarly, the known angles with the angle number given by the user and angle β are converted

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2	Lengths				0	<==ChRu	nScript("fb_	pos_initializ	ation.ch")	
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5	R2		4				Matrix(C5,			
6	R3		12				Matrix(C6,			
7	R4		7				Matrix(C7,			
8	Rp		5	-0-0-02	0	<==ChPut	Matrix(C4,	'rp")		
9										
	Known An	gle in De				and the second second second				-
	Theta1		10				tMatrix(C11			
	Beta		20		0	<==ChPut	Matrix(C12	,"beta")		
13						-				
	Unknown /									
	Theta Ang	le no	2				Matrix(C15			
	Angle		70		0	<==ChPut	Matrix(C16	,"angle")		
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23	Theta3		0.271302							
	Theta4		1.437659							
25										
26										
	Second so	olution	Radian							
	Theta1		0.003046							
	Theta2		1.22173							
	Theta3		-0.94483							
	Theta4		-2.11119					1 - XI	į.	
32								1	2	-

Fig. 3. A spreadsheet for four bar linkage position analysis with output.

to radian. The developer can also create an option by which the user can choose US customary or SI units to specify the link lengths. Furthermore, the relevant angles may be specified in degrees or radians by giving the user a choice The ChExcel function ChGetMatrix(C21:C24, ''theta_1") allows the user to display the values of array theta_1 for joint angles of different links in the Ch script in cells from C21 through C24 as shown in Fig. 3. These cell values can be changed according to the user input. Member functions set-Links() and setCouplerPoint() of class CFourbar build a four bar linkage with a coupler point. Member function angularPos() determines the angular position of every link from the given input. The configuration of a four bar linkage can also be displayed graphically using functions in the Ch Mechanism Toolkit.

Program 2. The script for angular position analysis of four bar linkage (fb_angularPos.ch)

thetal=thetal*M_PI/180; theta_ldeg[1]=thetal; theta_ldeg[angleno]=angle*M_PI/180; theta_2deg[1]=thetal; theta_2deg[angleno]=angle*M_PI/180; beta=beta*M_PI/180; fourbar.setLinks(rl, r2, r3, r4, thetal); fourbar.setCouplerPoint(rp, beta); fourbar.angularPos(theta_ldeg, theta_2deg,angleno); Fig. 3 is a snap shot of the Excel sheet after executing the script file "fb_angularpos.ch" in cell E20 and ChExcel functions in cells E21 and E22. The four bar linkage forms two circuits for the given θ_1 . The angles formed by the links in each circuit is given separately in an array in Ch. These two arrays can be displayed in proper cells as shown in Fig. 3. The angles displayed in cells "C21 to C24" are for the first circuit and "C28 to C31" for the second circuit. These script files are reusable and can be executed from different Excel sheets.

The Ch Mechanism Toolkit contains classes for design and analysis of the geared five bar mechanism, crank slider, four bar slider mechanism, Stephenson I and III mechanism and Watt I and II mechanism. The scripts associated with Excel spreadsheets executed in the back end use these classes to solve the design and analysis problems of different mechanisms.

4. An example of spreadsheet-based mechanism design and analysis

In this section, an example will be used to further illustrate some of the features and application of the spreadsheet-based mechanism design and analysis. For the comparison, the same problem presented in [21] is solved using spreadsheets in this section.

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35	Lower limit				0	0 <==ChGetMatrix(C36:D36,"inputlimitmax")				
36	Upper limit				0	<==ChGet	tMatrix(C4D	D40,"outp	outlimitmin")	
37					0	<==ChGet	Matrix(C41	:D41,"outp	outlimitmax")
38	Output Rar	ige								
39	Circuit (in deg)		Circuit 1	Circuit 2						
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44	Branch no		1		0	<==ChPut	Matrix(C44	,"branchno	ນ")	
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Fig. 4. A spreadsheet for analysis of a four bar mechanism.

Problem statement: The link lengths of a four bar linkage shown in Fig. 1 are given as follows: $r_1 = 12$ cm, $r_2 = 4$ cm, $r_3 = 12$ cm, and $r_4 = 7$ cm. The phase angle for the ground link is $\theta_1 = 10^\circ$. The coupler point *P* is defined by the distance $r_p = 5$ cm and constant angle $\beta = 20^\circ$. Determine the angular positions θ_3 and θ_4 as well as the position for coupler point *P* when the input angle $\theta_2 = 70^\circ$. Simulate the motion of the four bar linkage for its entire range of motion.

This problem can be quickly solved using the spreadsheet shown in Fig. 2 and its continuation in Fig. 4, which can be used as a template to solve other problems related to four bar linkage. After inputting the required parameters, the analysis is performed by executing the ChExcel functions in the cells of column E. The possible formation of two circuits is also considered and two sets of results are determined. These sets of two values are stored in two separate variables which are then displayed in Excel.

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35	Lower limit		0	0	0	<==ChG	etMatrix(C38	5:D36,"input	imitmax")		
36	Upper limit		360	360	0	Characteric C40:D40, "output limitmin")					
37					0	<pre>) <==ChGetMatrix(C41:D41,"outputlimitmax")</pre>					
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Fig. 5. A spreadsheet for analysis of a four bar mechanism with output.

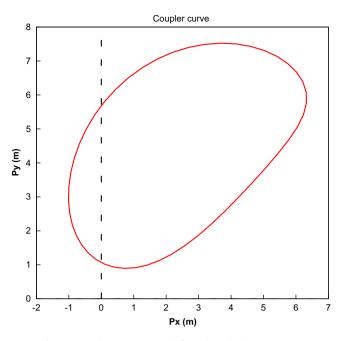


Fig. 6. A coupler curve generated from the script in Program 4.

The numerical results of the analysis are shown in Fig. 5 which is the continuation of the spreadsheet shown in Fig. 3. The angular ranges of the input and output links are determined using script file fb_getJointLimits.ch shown in Program 3. The member function CFourbar::getJointLimits() determines the range of the input link and the output link in unit of radian which are later converted to degree explicitly. It returns the type of four bar linkage. The variables fourbartype and i in Program 3 are declared in Program 1.

Program 3. The script for calculating the range of motion of four bar linkage (fb _get JointLimits. ch)

The four bar linkage analyzed is a crank-rocker with two circuits. The input range for θ_2 is a complete rotation with 360°. The output range for θ_4 is 77.98° $\leq \theta_4 \leq 150.15^\circ$ and $-130.16^\circ \leq \theta_4 \leq -57.98^\circ$ for the first and second circuits, respectively. When θ_2 is 70°, θ_3 and θ_4 are 0.2713 and 1.4376 radian, respectively, for the first circuit and -0.9948 and -2.1111 radian for the second circuit, respectively.

In addition to the values for θ_3 and θ_4 , the numerical output also displays the range of motion for the input/output links as well as the curve traced by the coupler point P for the first circuit of the four bar indicated by the branchno in Program 4 with its value obtained in cell E44 in Fig. 4. Upon the execution of script file fb_curve.ch in Program 4, it displays a coupler curve shown in

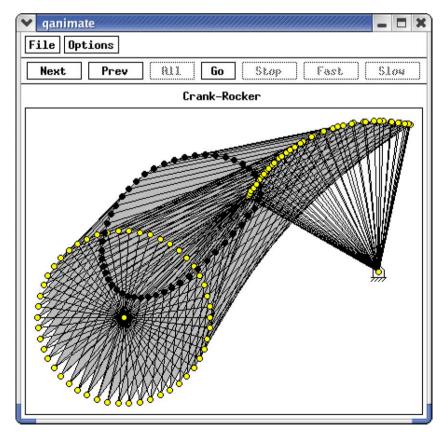


Fig. 7. All frames of four bar animation for the first branch.

Fig. 6, which is created by the member function fourbar.plotCouplerCurve().

Program 4. The script for plotting a coupler curve for four bar linkage (fb.curve.ch)

```
CPlot plot1;
fourbar.setLinks(rl,r2,r3,r4, thetal);
fourbar.setCouplerPoint(rp, beta);
fourbar.setNumPoints(50);
fourbar.plotCouplerCurve(&plot1, branchno);
```

The animation for the four bar linkage is generated for the specified circuit using the script file fb_animation.ch in Program 5. The member function call fourbar.setNumPoint(50) specifies 50 frames for the animation. The function call fourbar.animation(branchno) launches the animation for the specified branch by the integral value branchno. Fig. 7 shows an overlay of all the frames of animation for the first branch of the four bar mechanism.

Program 5. The script for animation of a four bar linkage (fb_animation.ch)

```
fourbar.setLinks(r1, r2, r3, r4, thetal);
fourbar.setCouplerPoint(rp, beta, TRACE_ON);
fourbar.setNumPoints(50);
fourbar.animation(branchno);
```

Note that the four bar specified in the above problem statement is a crank-rocker, which means that there are two distinct circuits for each input link position. Thus, the user can display either first or second circuit by selecting the branch number from the cell C44 and C49 in Fig. 4.

5. Conclusion

The Excel spreadsheet-based mechanism analysis and animation system, has been presented in this paper. The software package for spreadsheet-based mechanism analysis and animation system is developed using ChExcel and Ch Mechanism Toolkit. The package uses spreadsheets as the graphical user interface (GUI) and Ch scripts to perform computations. It can be readily used to perform relevant analysis and animation of various mechanisms including four bar linkage, crank-slider mechanism, five bar linkage, multi-loop six bar linkages such as four bar slider, Stephenson I and III, as well as Watt I and III. The system is open architecture. Users can extend the system for design and analysis of other mechanisms. The system contains salient features of both user friendly Excel interface and powerful computational capabilities of Ch, a C/C++ interpreter with high-level extensions for applications in engineering and science. A large number of software modules in Ch are readily available for spreadsheet-based applications. The ideas and concepts presented for spreadsheet-based mechanism design and analysis can be applied to solve many other engineering problems which can take advantage of the friendly user interface of Excel and computational power of C/C++.

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