KINEMATIC ANALYSIS OF PLANAR AND SPATIAL MECHANISMS USING MATPACK

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Abstract - *Mechanisms are found everywhere. A mechanism is a device designed to transform input forces and motions into a desired set of output forces and motions. For the analysis of mechanisms, many techniques are proposed in the literature. In this paper, Kinematic analysis of planar and spatial mechanisms is done using computational methods. Two, approaches namely, the vector formulation and the algebraic formulation are used to derive the velocity and acceleration equations of the mechanism. The approach of vector formulation is a popular approach and leads to simpler expressions for describing the motion of rigid bodies in both cartesian and polar notations. In this paper, a MATLAB based package named MATPACK has been developed for the numerical analysis of planar and spatial mechanisms. The planar mechanisms are analysed using the vector notation as proposed by Suh and Radcliffe [6]. The subroutines functions namely dyad, rotating guide and oscillating slider have been fully programmed in MATLAB. A notation given by Suh and Radcliffe, that provide an orderly transition from planar kinematics to the more complex geometry of spatial mechanisms was used. Denavit-Hartenberg notation has been developed for analysis of several types of multi and single-input spatial motion generator mechanism to have the correct order of output positions. Methods have been developed and given are the solution to this problem along with computational methods using MATLAB. Analytically, the position analysis of spatial mechanism is based on the Raven's method of independent position equations. Here in this paper, AUTOCAD 2018 is used for the determination of position vectors and orientation of links with respect to each other in three-dimensional space. For spatial mechanisms, a technique named the Denavit-Hartenberg parameters were used in order to find the velocity and acceleration using transformation matrices. Spatial mechanisms are generally much more difficult to design and analyse than planar mechanisms as they have complex motions associated with them and hence visualization is difficult in a 2-D plane. To make our work easier in visualizing isometric projections, the modelling is done by using CATIA v5 R20 software. Results are obtained in the form of a set of velocities and accelerations at a specified position at different orientations of the mechanisms. The results obtained from AUTOCAD 2018 are given as inputs for the MATPACK software. The MATPACK software acts a problem solver for analysis of planar and spatial mechanisms which gives accurate results. Results obtained from MATPACK are compared with theoretical/graphical results in this paper.*

Key Words: *Planar mechanism, Spatial Mechanism, MATPACK, Raven's method of independent position equations, Denavit-Hartenberg notation etc.*

1. INTRODUCTION

The modern era in mechanism design, along with the history of mechanical engineering as a distinct discipline, can be viewed as starting with James Watt. In the past, the powering of the machines is done by a single "prime mover" by mechanically connecting various machine components with linkages, shafts and gears. That tradition certainly predates Watt. The past century shows our ability to analyse and design mechanisms of increasingly complex polynomial systems. From this, we can expect that advance in computer algebra and numerical continuation for the derivation and solution of the even more complex polynomial systems will advance research in mechanisms.

Now examining recent research, we can identify one which is emerging out with research trends that we can expect to persist into the future i.e. the analysis of spatial mechanisms and robotics systems. In each case, we find that researchers are formulating and solving polynomial systems of total degrees that dwarf those associated with major kinematics problems of the previous century.

In early 2000's, A. J. Sommese and C. W. Wampler published their text on the mathematical theory of polynomial continuation and its applications to systems that arise in engineering and science, which they term "numerical algebraic geometry". By 2008, at computation speeds of 1500 paths per second RRS problem could be achieved on a PC in 5 minutes.

The computational resources are not available until 1994 for solving the problems which occurred in spatial mechanisms. Continued improvements in processing speed, parallel processing architectures, and algorithm efficiency have the potential to yield such rapid solution of very large polynomial systems can become practical and routine.

1.1 Literature Review

The study is about kinematic analysis of planar and spatial mechanisms using computers and regarding Denavit-Hartenberg parameters. Research articles concerning these issues are summarized and discussed in this project review.
Joseph E. Shigley et al. [1] in his book uses conventional methods of vector analysis in deriving and presenting the governing equations in their solution and briefly present an introduction to Denavit and Hartenberg's methods using transformation matrices.

George N. Sandor et al. [2] discusses about relative screw motion between links or as constraining the motion of the two chains of the mechanism connected to the two elements of the pair.

Ettore Pennestri [3] developed a tool for third order kinematic analysis of spatial mechanisms. This paper describes a maple program for the generation in symbolic form of all the equations needed for the kinematic analysis, up to the third order, of a large class of spatial mechanisms.

W. P. Boyle [4] in his paper presented a pseudographical technique, in conjunction with an equation solving software, is used for an analysis of the kinematics of a 3-D spatial four bar linkage.

J. Michael McCarthy [5] surveys on Kinematics, Polynomials, and Computers relating issues. The goal of this survey is to show that in the past century our ability to analyse and design mechanisms and robotic systems of increasing complexity has depended on our ability to derive and solve the associated increasingly complex polynomial systems.

C. H. Suh et al. [6] explains in his book that the development of theory and methods for analysis and synthesis of spatial mechanisms proceeded rapidly after 1930. This book carries out the algebraic vector or matrix operations to form an algorithm for the problem. This algorithm can be coded in FORTRAN and tested, using numerical results published with many examples given.

G. K. Ananthasuresh et al. [7] investigates on a closed form solution of the analysis of the RSCR (Revolute-Spherical-Cylindrical- Revolute) spatial mechanism. This work is based on the geometric characteristics of the mechanism involving the following three cases: the cone, the cylinder, and the one-sheet hyperboloid.

Michael Barton et al. [8] presented a general kinematics simulator that allows end users to define planar and/or spatial arrangements, even along freeform curves and surfaces. The mechanical arrangement is then converted into a set of algebraic constraints and the motion of the arrangements is computed with the aid of a multivariate polynomial constraint solver.
David Ferng Chy [9] in his paper studied on Analysis Of R-S-S-R Spatial Four-Bar Mechanism. The analysis described in this paper is developed basically by using tensor notations and operations, and the calculations take advantage of the capabilities of modern digital computers. A FORTRAN program for the IBM 360 Data Processing System which will analyse the displacement of each joint pairs, angular velocity, and angular acceleration of the output link is included.

Jiegao Wang [10] proposes a new approach for the dynamic analysis of parallel mechanisms or manipulators. This approach is based on the principle of virtual work. As compared to the conventional approach of Newton-Euler. The new approach will lead to a faster algorithm for derivation of the generalized forces: which is useful for the control of a mechanism or manipulator.

1.2 Objective of the Work

Advances in algorithm and computer speed have brought about a new paradigm in kinematics. The proportion of effort one must exert in heavy manipulations of algebraic expressions is greatly diminished through the use of computer algorithm, so as to analyse a geometrically constrained motion or to design a device, to produce desired motions. This paper briefly summarizes how numerical algebraic geometry and a computational approach based on polynomial continuation, can be applied for solving such problems.

This paper introduces the existing notation and methods that provide an orderly transition from planar kinematics to the more complex geometry of spatial mechanisms using MATPACK software. For the analysis of spatial mechanisms, the position vectors were found from a graphical analysis done on an AutoCAD software system. Considering the complexity involved in orientations for spherical joints in spatial mechanisms for validating D-H parameters, here, we have given a solution to those tedious problems by solving it using AutoCAD software.

2. 2D AND 3D MODELLING

When the topology of the mechanism is complex, it is tedious to carry out by hand all the algebraic operations needed for the deduction of the analysis equations. A possible alternative is the use of general-purpose multibody programs. A potential user of this program needs only to specify, for each kinematic pair, the type, the two-body connected, the coordinates of some reference points in the two body fixed reference systems and the time dependent driving constraints.

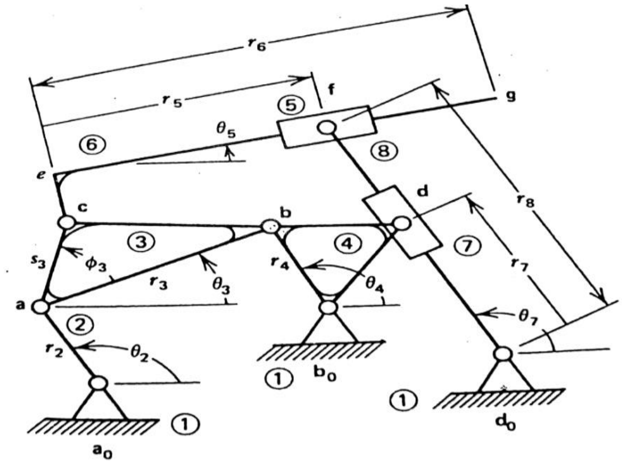

Figure 1. An example of a multi-element plane mechanism that involves basic kinematic elements.

A general-purpose computer program based on the algebraic formulation approach can be developed. The equations for the kinematic analysis of spatial mechanisms are often required by industrial designers. The purpose of this project is to develop a general computer aided package along with the technique which can be otherwise used for the analysis of spatial mechanisms.

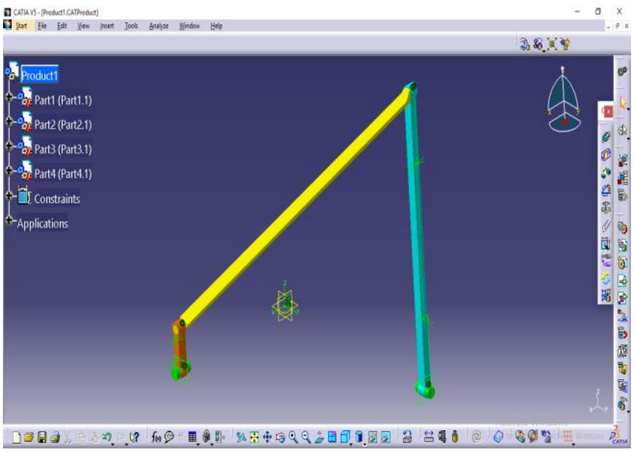

Figure 2. Spatial RRRR mechanism

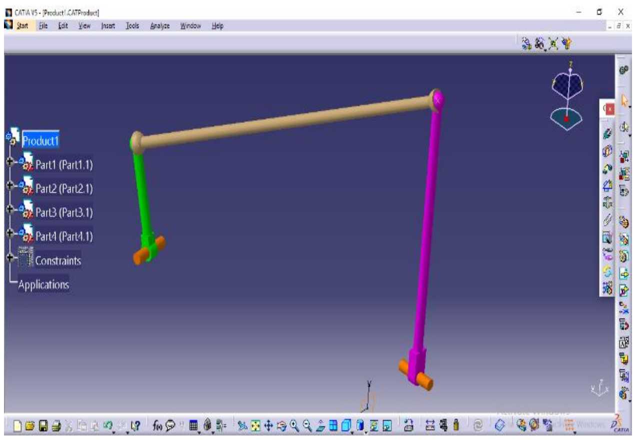

Figure 3. Spatial RGGR mechanism

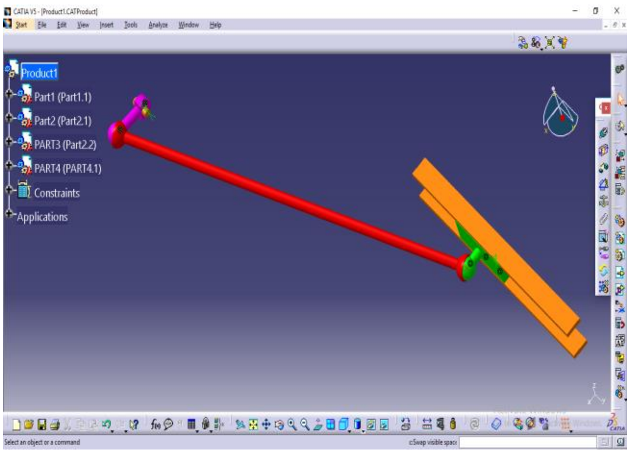

Figure 4. Spatial RGGP mechanism

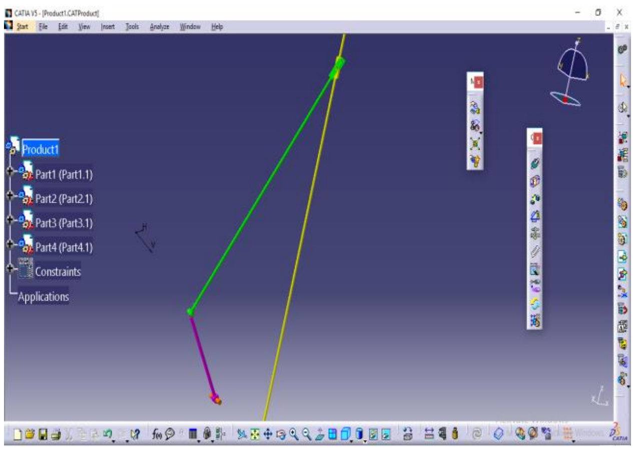

Figure 5. Spatial RGRC mechanism

3. DENAVIT-HARTENBERG CONVENTION

The transformation equations are dealt only with three-dimensional rotations about a fixed point. Yet the same approach can be generalized to include both translations and rotations, and thus to treat general spatial motions. Most modern work on this approach stems from the work of Denavit and Hartenberg, who developed a notational scheme for labelling all single-loop lower pair linkages and also devised a transformation matrix technique for their analysis. Assigning a coordinate frame and a coordinate system is important in case of spatial mechanisms because of the complexity involved in it.

The key to Denavit-Hartenberg approach comes in the standard method they defined for determining the shapes of the links. The relative position and orientation of any two consecutive coordinate systems placed as described above can be defined by four parameters labelled a,α,θ, and s shown in Fig.4.3 and defined as follows:
$a_{i,i+1}$ = distance along X_{i+1} from Z_i to Z_{i+1} with sign taken from the sense of X_{i+1}
$\alpha_{i,i+1}$ = angle from positive Z_i to positive Z_{i+1} taken counter clockwise as seen positive x_{i+1}

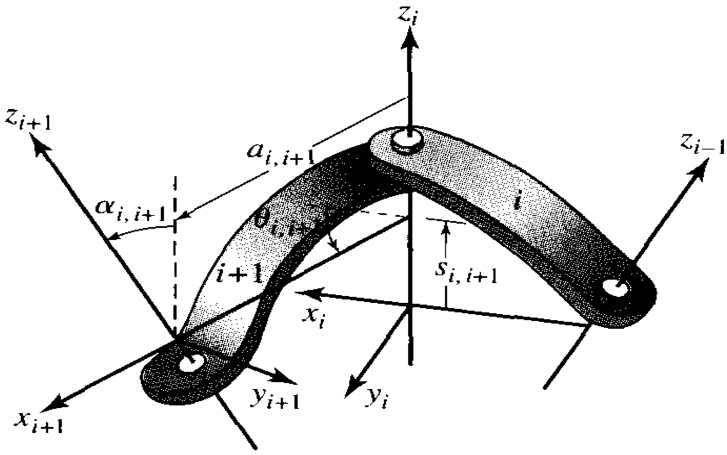

Figure 6. Definitions of Denavit -Hartenberg parameters

$\theta_{i,i+1}$ = angle from positive x_i to positive x_{i+1} taken counter clockwise as seen positive z_{i+1}
$s_{i,i+1}$ = distance along Z_i from x_i to x_{i+1} with sign taken from the sense of Z_i

4. RESULTS AND DISCUSSIONS

Regarding computational analysis of planar and spatial mechanisms, one problem is the complexity of the solution procedure, which is often caused by improper problem formulation. Another problem is the handling of constraint conditions such as mobility. To cope with the problems like these, we need to develop new concepts in the analysis procedures, and review the conventional approaches. This motivates the research reported in this paper.

Table 1. Comparison of theoretical results with MATLAB results for spatial RRRR mechanism at a definite position

RESULTS OF RRRR MECHANISM	ω_3 (rad/s)	ω_4 (rad/s)	α_4(rad/s²)
THEORETICAL RESULTS	8.820	10.797	130
MATLAB RESULTS	8.8148	10.7950	129.825

Table 2. Comparison of theoretical results with MATLAB results for spatial RGGR mechanism at a definite position.

RESULTS OF RGGR MECHANISM	V_B (mm/s)	A_B(mm/s²)	ω_4(rad/s)	α_4(rad/s²)
THEORETICAL RESULTS	254.6817	10808.4298	− 25.468	− 864.59
MATLAB RESULTS	254.5243	10793.6211	-25.452	-863.404

Table 3. Comparison of theoretical results with MATLAB results for spatial RGGP mechanism at a definite position

RESULTS OF RGGP MECHANISM	V_B(mm/s)	ω_3(rad/s)
THEORETICAL RESULTS	345.4	7.9253
MATLAB RESULTS	335.3396	7.2731

Table 4. Comparison of theoretical results with MATLAB results for spatial RGRC mechanism at a definite position

RESULTS OF RGRC MECHANISM	V_B(mm/s)	ω_4(rad/s)
THEORETICAL RESULTS	2808.95	19.444
MATLAB RESULTS	2809.0	19.44518

5. CONCLUSIONS

Vector and matrix notations offer a convenient and compact means for expressing relationship for both planar and spatial mechanisms. They provide value addition to the existing methods like graphical methods for analysis of linkage. In this thesis, an attempt is made for kinematic analysis of planar and spatial mechanisms using MATPACK, a package developed using MATLAB in generalized functions. This thesis uses vector, matrix and Denavit- Hartenberg Notations while developing the algebraic equations necessary for the analysis of planar and spatial mechanisms. AutoCAD 2018 was used for analysing the link positions and CATIA v5 R20 software is used for visualization purposes.

For planar mechanisms, animation validating the solution obtained using MATPACK is performed in MATLAB itself. For spatial mechanisms, CATIA v5 R20 is used to compare the numerical solution obtained using MATPACK with that given by graphical means. The results are found to be quite close. Care has been taken in development of MATPACK software so that it is general in nature and can be used for solution of any planar and spatial mechanisms. A potential user of this program needs to specify his inputs in a simple formatted fashion. The format includes, the number of links, co-ordinates of all joints, the type of joints which form the links, etc.

While analysing different spatial mechanisms by using D-H parameters certain limitations are observed. For analysis of spherical joint by D-H parameter, spherical joint is considered as revolute joint. So, multiple degree of freedom is constrained and considered as single degree of freedom for simplification purpose, so here there is a scope to analyse spatial mechanism with spherical joint using D-H parameters. Also, once the frames are fixed and the parameters identified, it is simpler and an easy way to completely specify the mechanism and to find the relationship between any two frames on the mechanism.

For spatial mechanisms, position analysis has been performed using AutoCAD to avoid the solution of higher order polynomials associated with the position equations. The output from AUTOCAD 2018 is given as inputs to MATPACK software. It is observed that comparison made between MATPACK results and theoretical/graphical results are accurate within 0.05% error. Results of comparison are tabulated.

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