Mechanism design with Analytix

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Introduction

Traditional dynamics software packages, while powerful in their analysis capabilities are somewhat lacking in their ease of use. They are most suitable for use when a design is complete to perform "soft prototyping" of a mechanism. In practice they are typically used by expert analysts who have been extensively trained on the software. Mechanism synthesis packages, on the other hand, while easy to use, are limited in the types of problems which they are designed to handle.

A third type of package which has recently emerged as a tool for the early or "conceptual" phase of mechanical design is the variational geometry system. In this paper, we describe a variational geometry approach to mechanism design and analysis. The technical basis for this approach is a new method for solving constraint systems, called "Constructive Variational Geometry". [1,2] This method lends itself to incorporating engineering mechanics into a variational geometry system and provides an extremely flexible and easy to use tool for the conceptual phase of mechanism design.

Mechanism design with variational geometry

In this section, we describe how such a system appears to the user. In particular, we describe the Analytix mechanism design package developed by Saltire Software.

To create a model of a mechanism in the Analytix package, the user first sketches the mechanism. Typically the sketch contains a simplified representation of the mechanism's geometry. Links are usually represented by straight lines between joints or points of force application. Centers of gravity of any links with non-negligible mass are explicitly sketched.

The user then specifies the exact geometry by adding constraints to the drawing. The constraints specify angles or distances on the drawing. For a kinematic analysis, the constraints should represent quantities whose motion is known. In practice, for a single degree of freedom mechanism, all the constraints but one represent quantities which stay fixed throughout the motion of the mechanism. The final constraint represents the driver, whose motion is known.

The Analytix system aids the constraint specification process by giving continuous feedback on whether the model is underconstrained, overconstrained, or consistently constrained.

To perform a kinematic analysis, the user specifies the velocities and accelerations of any constraints which are in motion. The user also must specify a fixed point and a fixed line.

With the constraint velocities and accelerations given, the model is able to output on demand the position, velocity, and acceleration of any point of the mechanism and the angular velocity and angular acceleration of any line.

Static analysis of a mechanism may be performed in a very natural way in a Variational Geometry system by assuming that constraints carry reactions. Hence not only the motion, but also the statics of the model are defined by the constraints. If loads are applied to a mechanism in Analytix, reaction forces are generated in the constraints. The system will sum the constraint forces which impinge on a point to give the reaction force at that point. The system will integrate the forces on a single line segment to give shear force and bending moment.

Analytix allows external forces to be applied to any point on a mechanism and external torques to be applied to any line. These forces may be constant or they may vary with geometry, time or some other parameter. Analytix also provides conformal force elements: translational and rotational spring-damper-actuators.

To perform inverse dynamics in Analytix, the user specifies the instantaneous motion of the mechanism in the same way as for kinematics, but also applies forces and specifies the mass of points representing mass centers. The user also specifies the moment of inertia of lines which represent rigid links. The user can now generate the same reaction force outputs as for the static analysis, except the inertial forces generated by the accelerating masses will be taken into consideration.

In a dynamic analysis, some constraints represent quantities whose behavior is known in advance - either quantities which remain fixed or drivers, whose motion is given. Other constraints are free to accelerate in response to unbalanced forces present in the model. To set up a dynamic model, the user specifies the fixed constraints and the input drivers in the same way as for kinematic analysis. Free constraints are given initial values and initial velocities and marked as being free to accelerate. The user then specifies a time interval over which the motion is to be integrated and an interval at which snapshots of the motion are to be taken.

The result of the dynamic analysis is a sequence of models, each of which represents a single instant of the motion. These models may be interrogated individually or as a group for any of the kinematic or reaction force outputs mentioned above. This provides the user with a high level of interactivity in the manipulation of the results of a simulation.

An advantage of a constraint based mechanism design package is the ease with which the flexibility of the software may be enhanced by integrating general purpose mathematical tools with the special purpose mechanical tools described above. For example, the Analytix program provides an equation calculator with a two way link to the geometry and mechanics of the model. Expressions generated in the calculator can be used as input forces or constraint values for the model. Conversely, geometry, velocities, accelerations or reaction forces from the model may be used in the equation calculator. In addition, a numerical root finding capability is provided.

Having the general purpose mathematical tools with full access to the mechanical model provides a powerful capability for the user to manipulate his mechanism design and is a strong advantage to the variational geometry approach.

Model iteration

Because of its Variational Geometry design, Analytix provides an extremely powerful platform for iterating the mechanism model in order to achieve an optimal design. For example, engineers at Camloc, an English gas spring manufacturer, have used Analytix to help them optimize placement of springs in clients' designs.

Before acquiring Analytix, engineers at Camloc were figuring by hand the moment calculations needed to select springs for new applications. Typically, they knew the geometry of the object that the spring would be lifting, as well as its weight and center of gravity. They also knew where the spring should be mounted in relation to the center of gravity. They then calculated the amount of force required in the spring to lift the particular object. This was not too difficult, but hand calculations limited them when they wanted to optimize spring selection by exploring other mounting possibilities.

Depending on where a spring is placed, different forces are needed to lift the same weight. The nearer a gas spring is mounted to the pivot position, for instance, the more force it needs to produce to lift a certain weight. By investigating different mounting positions, engineers can decide which spring would be the best for a particular application. To balance the appropriate amount of force with other selection factors such as spring size and cost was taking three to four days using hand calculations, when it was possible. In situations where they had to fit the spring around particularly complex geometry, it was impossible to consider all the possibilities because there was not enough time.

With the use of Analytix, spring optimization can be done in only one day even for applications with complex geometry. The main benefit of Analytix, however, is the ability to easily modify geometry and rerun the analysis as many times as needed to investigate different mounting positions. The three to four days needed to optimize a spring by hand has been reduced to one day using Analytix, even though the engineers try many more iterations. The ease of modeling with Analytix makes it possible to add more intelligence to the model, as well, by adding extra details of parts and features that would not have been attempted when using hand calculations. This gives more accuracy to the model, and gives engineers the confidence that they have modeled real-world behavior.

Front end to software prototyping

Analytix' readily accessible 2 D parametric mechanism analysis makes it a suitable tool for use as a front end to more elaborate 3D software prototyping programs. For example, in the

Naval Surface Warfare Center in Dahlgren, Analytix fits nicely into the Engineering Analysis Group's environment.

Although the group has 3D dynamics packages, many projects do not require the investment of a detailed 3D study. In general, Analytix is used by project engineers for quick looks at design concepts, what-if studies, or whenever a quick layout sketch is needed to investigate fit or kinematics. In studies of systems that open and close missile launcher hatches, for instance, the combination of a quick 2D analysis tool and a more detailed 3D program was very beneficial. Most hatch systems operate under automatic control where an electric motor operates a complex linkage. The timeline for this system is very tight and small design changes can have a big effect on whether it stays within the specification. In one project, the engineer needed to adjust the linkage design to improve the alignment of the hatch when closed. The initial studies were done with PC based software including Analytix to quickly investigate different configurations. Then a higher fidelity three dimensional model was developed by analysis specialists, using Mechanica in this case, for a complete simulation of the final design. Having a tool to use for the quick look studies allowed the project engineer to rapidly develop a design for the detailed timeline analysis. Without the ability to do the what-if analysis the opportunity to optimize the design would have been lost.

Up front tolerance analysis

Manufacturing issues are frequently neglected in the initial mechanism design process. This may prove costly, however, when errors in tolerance specifications imply that production mechanisms do not function as required.

Analytix provides a number of tools for incorporating tolerance analysis into the initial mechanism design process. Driven by input tolerances on dimensions, tolerance stack-up on output distances or angles are computed, using either statistical (RSS) or worst case stack up. In addition a percentage contribution analysis is performed, which lets the designer pinpoint which input tolerances are most influential in their effect on the stack-up. Tolerance zones may be computed which show the region where a point may lie under the given (statistical or absolute) tolerancing. Tolerance zones for coupler curves may even be computed.

A practical example is provided by a small part of a circuit breaker designed by Siemens Energy Automation in Atlanta GA. The purpose of the linkage is to change linear motion at the button on the front of the breaker, to rotational motion several inches away inside the breaker. While the mechanism is simple, the tolerance issues involved are complex. On the first developmental prototypes the button stayed against the paddle holding the breaker open. It appeared that the paddle height dimension had to be changed to alleviate the interference. The layout showed that nominally there seemed to be adequate clearance and the parts should not be in contact. Instead of simply changing the dimensions based on empirical data, a tolerance study was performed. The tolerance study of the button position was straight forward since all of the dimensions were linear and in a straight line. The tolerance study of the linkage was not easy to calculate manually. The use of Analytix avoided a potential interference that may not have been found using conventional techniques. Drawing and dimensioning this assembly in Analytix showed in the starting position that the distance from the bottom of the button to the top of the paddle was 0.072 inch with an absolute tolerance of ą0.107 inch. It was quite a surprise to find that the

tolerance was so large. This showed that it was possible to have no clearance between the parts. Care had to be taken at this point since the button had a fixed amount of travel possible and the paddle had to fall within that range. Few designers would realize that tolerances of this magnitude would be involved, and calculating this stack-up is very time-consuming because of the need to change linear tolerances into angular tolerances, back to linear tolerances and
finally back to angular tolerances.

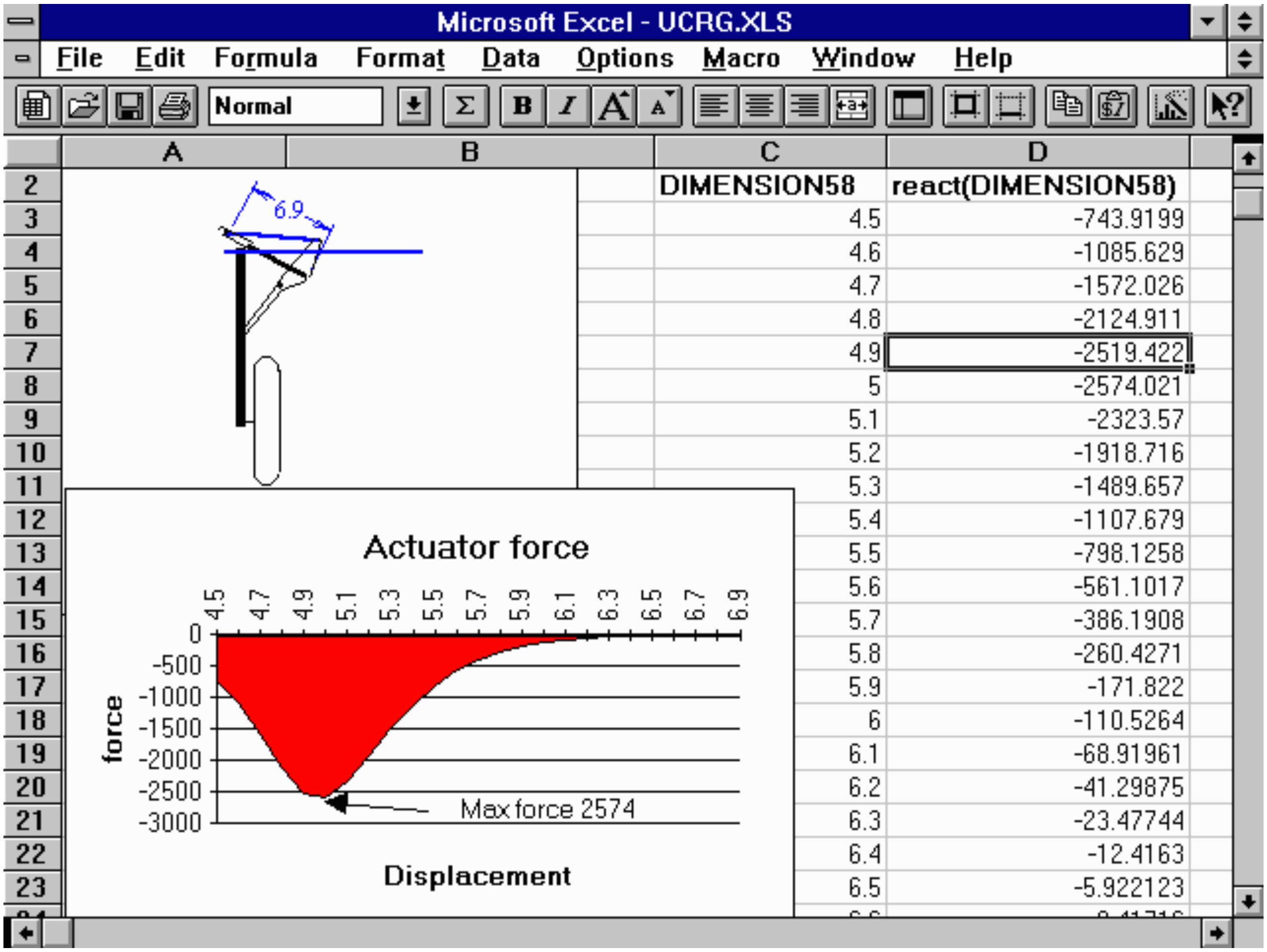
Integration with other design tools

A critical aspect of an up-front mechanism design package is a capability to integrate with the other computer tools used by the engineer. Typically, the engineer uses a word processor, a CAD package and a mathematical analysis package. The mathematical analysis package may be a spreadsheet, such as Microsoft Excel or Lotus 123, or a free form math package such as Mathcad. Analytix provides a number of different ways of linking with these other computer tools.

Analytix is an OLE Server Application. This means that the user can embed a live drawing of his mechanism into a Windows based Word Processor. When he double clicks on the drawing, Analytix is invoked to let him edit the drawing and modify his design.

DXF input and output of geometry provide a first level of link with CAD packages. Dynamic Data Exchange (DDE) however provides the capability of creating a hot link between Analytix and a Windows based CAD package.

Because Mathcad is such a widespread tool in the engineering world, Saltire Software have built a custom link which allows Analytix models to be embedded in Mathcad documents and which, furthermore, allows active links to be maintained between Mathcad variables and input or output parameters of the geometry. This lets the user combine the full mathematical capabilities of Mathcad with the mechanics capabilities of Analytix.



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6.3	-23.47744
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Figure 1: An Analytix model embedded, using OLE, in an Excel document

Cams

An important aspect in the design of machinery is the design and analysis of cams and cam driven motion. There are a number of different ways in which it is desirable to define cams. In some situations, the cam is defined as a sequence of piecewise smooth functions describing different segments of the desired motion and joined with continuous acceleration curves. In other cases, the cam profile is known and the follower motion is desired. In still other cases, the downstream motion of a mechanism is known and it is desired to synthesize a cam to drive the motion.

Analytix/Cams, the cam design module of Analytix, allows a cam to be defined either in terms of follower motion or in terms of cam geometry. Follower motions may even be derived from analysis of a downstream linkage in Analytix and pasted into the cam design dialog.

The kinematics and dynamics of the entire cam driven mechanism may be analyzed in Analytix. Because the relationship between cam and follower is established analytically up front, this downstream analysis is extremely efficient.

Symbolic Mechanics

A symbolic mechanics system has been built by Saltire Software as an additional module to the Analytix package. This symbolic system creates mathematical descriptions of engineering mechanics problems expressed as Analytix models. The mathematical descriptions may be analyzed using the Maple symbolic mathematics package, or turned into C or Fortran subroutines for use in numerical simulations or numerical control applications.

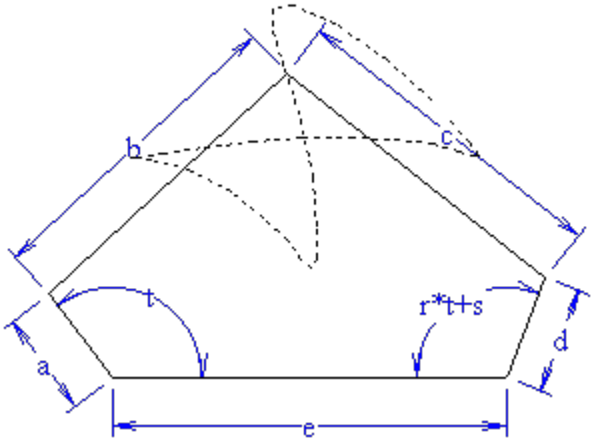

Figure 2: An Analytix model of a geared 5-bar linkage.

For example, we derive equations for the curve traced by one point on a geared five bar linkage. A gear pair is modeled in Analytix by creating a formula linking the values of two angles. In Figure 2, one angle is given a value t, while a second angle is given a value r*t+s. r is the gear ratio, s represents the offset between the gear angles in an initial configuration.

Table 3 gives the expressions derived by the system for the coupler curve drawn in figure 2.

$$P8y = d\sin(r\,t + s)$$

$$L10B = \cos(r\,t + s)$$

$$P8x = e - d\,L10B$$

$$P6d^2 = (P8x - a\cos(t))^2 + (P8y - a\sin(t))^2$$

$$P6c = \frac{1}{2}\,\frac{P6d^2 + b^2 - c^2}{P6d}$$

$$P6e^2 = b^2 - \frac{1}{4}\,\frac{\left(P6d^2 + b^2 - c^2\right)^2}{P6d^2}$$

$$P6y = a\sin(t) + \frac{P6c\,(P8y - a\sin(t))}{P6d} + \frac{P6e\,(P8x - a\cos(t))}{P6d}$$

$$P6x = a\cos(t) + \frac{P6c\,(P8x - a\cos(t))}{P6d} - \frac{P6e\,(P8y - a\sin(t))}{P6d}$$

Table 3: Equations for the coordinates of the coupler curve for the geared five-bar linkage

Examples

In this section, we give examples of the use of the variational geometry system in mechanism design problems. Our goal in presenting these examples is both to show how the constraint based mechanism package is used in practice, and also to exemplify how the general purpose equation solution capabilities enhance the flexibility of the tool for solving real world problems.

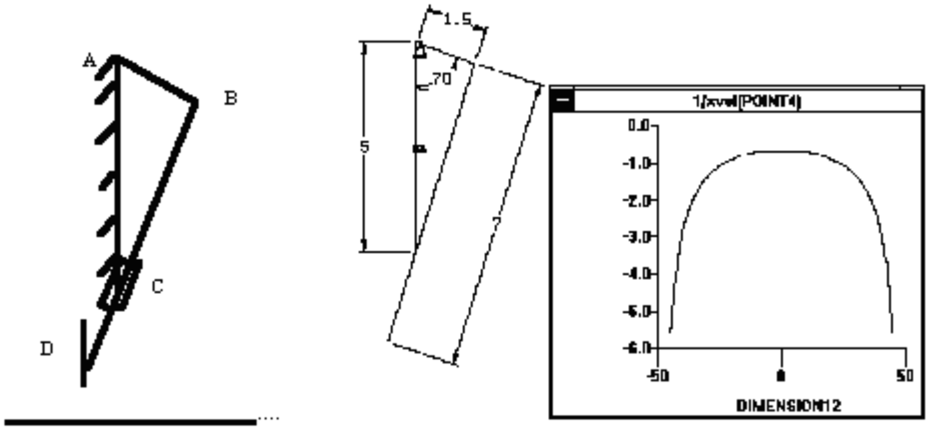

Figure 4: Analytix model of a "flying blade" mechanism

The first example (figure 4) is in the design of a cutting tool for use with a conveyor belt. The mechanism is driven by a stepper motor at A which turns the crank AB. Line BD is constrained to slide through point C, which is fixed with respect to point A. In order to match the speed of the conveyor belt, we require the horizontal component of the velocity of D to be constant through the cutting phase of the motion. The problem we wish to address is to derive a velocity profile for the stepper motor which gives a unit horizontal velocity component to D.

Figure 4b shows a variational model of this mechanism. The angle CAB is given unit angular velocity and the x component of the velocity of D may be output. The desired input angular velocity is w = 1/xvel(D). This output function may be simply tabulated or graphed in Analytix.

Our second example (figure 5) is a parallel lift mechanism, where a mass positioned at point E is counteracted by a spring/damper between points F and G. We wish to examine the dynamic response of this mechanism when it is perturbed about its position of static equilibrium. First we need to find the position of static equilibrium.

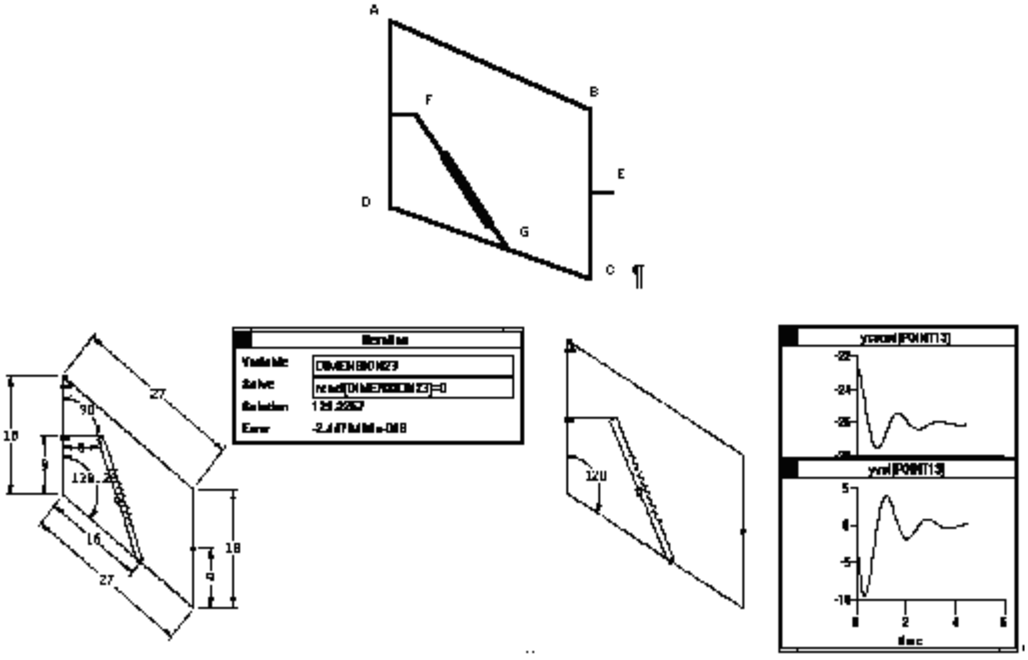

Figure 5: Static equilibrium and dynamic simulation for a parallel lift mechanism

A variational geometry model of this mechanism is shown in figure 5. The model specifies the lengths of the various members, and also specifies an angle. The angle does not represent a physical restraint but rather parameterizes the position of the lift. The static model used by the variational geometry system, however assumes the presence of a reaction torque in this angle in order to maintain equilibrium at the given angle value. In real life, however, there is no moment bearing structure at this joint, hence for static equilibrium the angle value must be such that no reaction force is present in the constraint. To find the equilibrium configuration, therefore, we need to find the value of the angle such that its reaction torque is zero. The root finder in Analytix may be used to find this value (figure 5b).

To examine the dynamic response of this model, we specify that the angle is free to move and give it an initial value perturbed from the equilibrium value (figure 5c).

Discussion

Although kinematics and dynamics software has been available for well over a decade, practical mechanism design is still frequently practiced with pencil and paper, with hardware prototypes, or with the limited computer assistance of a CAD package. One reason for this is that conventional dynamics software is rather difficult to learn and non- interactive in its application. It is thus perceived as applicable only to the most complex of dynamics problems and not to the simple problems routinely addressed by the design engineer.

A variational geometry model consists of a sketch with constraint values specified on the sketch. This model of geometry corresponds closely to the natural mode in which the geometry of engineering problems is expressed, and is thus a very easy user interface for the engineer to learn. Further, it is extremely easy to modify a constraint based geometry description either by manual intervention or as part of some numerical analysis procedure. This ensures that the software is flexible enough to be of use in a wide range of real-world situations, some not within the pure domain of mechanism analysis.

References

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2. Todd P. (1992) "A Constructive Variational Geometry Based Mechanism Design Software Package" ASME DE-Vol 46, *Mechanism Design & Synthesis*, pp 267 - 273