Teaching Mechanism Design Using Constraint-Based Design Tools in a CAD System

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Abstract

This paper describes the use of a CAD system with parametric design capabilities to synthesize and analyze planar mechanisms. The techniques used have been developed and used in a third-year course entitled Dynamics of Machines. Geometric and dimensional constraints are applied to the skeleton diagram of a linkage created using standard graphical synthesis methods. The constraints used to emulate the behavior of different types of joints are discussed. The constraints are applied to the skeleton diagram in a way that allows simulation of the operation of the mechanism. The paths of key points such as coupler points can be plotted as part of the simulation. The use of algebraic constraints to impose relations between parameters is also discussed. All of the techniques described will be demonstrated in the presentation.

1. Introduction

Graphical techniques have long been a necessary tool for the mechanism designer. Synthesis techniques based on geometric constructions are traditionally followed by analysis which include finding extreme positions as well as drawing the mechanism in a large number of positions throughout its full range of motion. [1] This form of position analysis can then be followed by graphical analysis of velocities and accelerations. Complete analysis requires that the process be repeated at each position throughout the motion. The use of CAD systems in this graphical approach greatly reduces the time and labor required and should encourage the designer to explore alternative solutions more extensively. Specifically, constraint-based, or parametric design tools make the process easier and quicker by eliminating the need to re-draw elements of the mechanism, even when changing their dimensions.

Constraint-based design is a term used to describe a technique which allows the designer to experiment with design changes while maintaining a set of imposed limits or constraints. It is also used to describe the technique of varying constraints in order to assess their effect on the function of the system being designed. Constraints may include factors such as size, weight, relationships between elements, types of materials, cost, and function. In this context, designing linkages for a particular purpose, we will focus on the sizes of elements and relationships between those elements.

The constraints we will consider can be divided into three basic categories: geometric;

dimensional; and algebraic. Examples of each category are listed below:

Geometric Constraints:
- Intersections
- Direction in space
- Location in space
- Parallelism
- Perpendicularity
- Tangency
- Coincidence
- Concentricity
- Points on elements

Dimensional Constraints:
- Length of elements
- Distance between points
- Angles

Algebraic Constraints:
- Assignment of variables (association of a parameter with a dimension)
- Equations relating parameters
- Inequalities involving parameters

The CAD software currently used in this course is MicroStation SE ®. This is the software used in our Engineering Graphics courses so that the students are already experienced in its use. Similar tools are available in other software packages. MicroStation provides a tool for applying each of the types of constraint listed. When constraint dimensions are placed, the user has the option of assigning a name to the dimension at the same time, or this association can be made after the fact.

We will begin by showing how to use the CAD tools to construct a working model of a simple planar linkage.   The individual tools will be discussed as they are used to construct a model of a four-bar linkage.

2. Modeling a 4-bar linkage

This section describes a step-by-step procedure which creates a parametric model of a 4-bar linkage. This model can be manipulated in exactly the same way as a physical model, but with the advantages that its dimensions can be easily changed and that it can produce accurate quantitative information about the linkage.

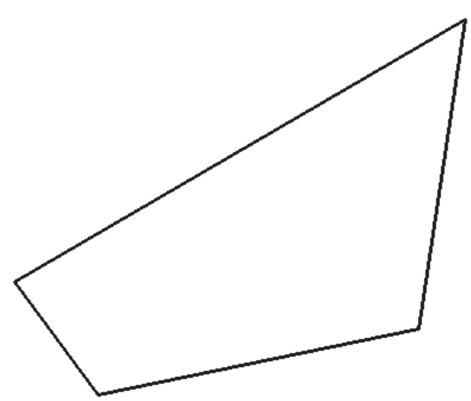

Figure 1. Sketch of the kinematic diagram for a four-bar linkage.

The first step is to create a sketch of the linkage using individual lines.   Line strings or polygons may behave differently when we apply geometric constraints. It is convenient to sketch the linkage to be approximately the desired size, but specific dimensions will be controlled by constraints. Sketching the ground link at an angle allows us to easily control the relative locations of the ground points. A typical linkage is shown in Figure 2.

The application of constraints to the mechanism begins by creating a constraint point at the location of each joint in the mechanism. We do this by constraining a point to lie at the intersection of each pair of adjoining links. Systems may differ, but MicroStation creates graphic elements which represent the constrained points. This point will move with the intersection if the elements are moved.   An intersection constraint point must be created for each of the four joints in the linkage.

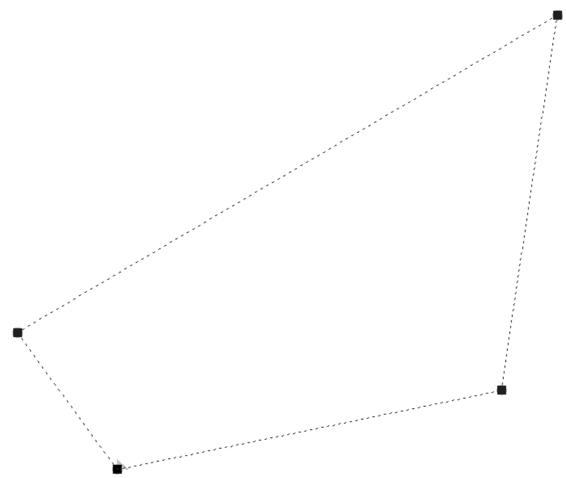

Figure 2.. Sketch of mechanisms with intersection points at each joint. The lower left-hand joint is anchored in space. The original lines have been replaced by dashed construction elements and small squares represent the intersection points.

One of the joints is selected to be the ground point of the driver link. We constrain this point so that it cannot change its location in space. Again, a geometric element (in this case a triangle) is created to represent the constraint. At this point, it is a good idea to make sure that all of the constraints which we have applied are working correctly. Attempting to move the driver link should cause the link to rotate about the fixed point at the lower left-hand corner of the figure. Note that the other links may also move and the lengths of lines may change, but the in tersection points should always maintain their correct relationships to the intersecting lines.   At this point, manipulating each element in turn allows the designer to observe how the constraints work.

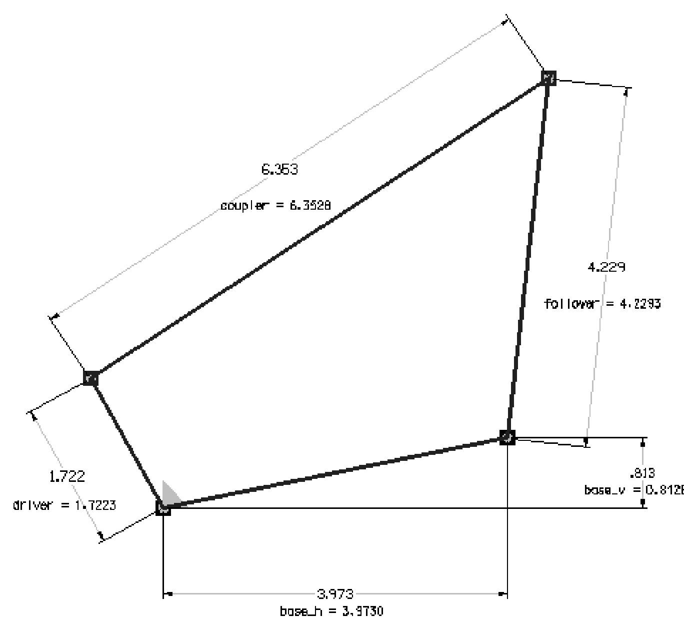

Figure 3. Completely dimensioned model of linkage.

Clear visualization of the mechanism requires attaching graphic elements to represent the linkage. A line string or polygon can be created with its vertices constrained to coincide with the intersection points at the joints. The figure does not yet represent a mechanism since the lengths of the links are not fixed.

The length of each link by applying dimensional constraints. Dimensional constraints are applied by dimensioning either the sides of the figure created in the previous step or the distance between the joints defining the link. Alignment of dimensions is important. Using view or coordinate system alignment controls the components of a line while true alignment controls the length of a line. The dimensioned model is shown in Figure 3. Components were used to define the ground link so that the designer specifies the coordinates of one ground point relative to the other. It is also important NOT to dimension the original lines since their lengths are fixed. Their only function is to define the intersection points. The figure also shows the names of the parameters which we have assigned to the dimensions.

We have now completely defined a model of the mechanism. Repositioning the driver now should cause it to rotate without changing length and the rest of the mechanism should now follow the driver just as the actual mechanism would. Changing the dimensions graphically allows the designer to quickly test the effect of changes.

Once satisfactory operation of the mechanism has been achieved, the designer can apply precise values to the dimensions. MicroStation allows the designer to specify precise values for any dimension either through a special tool for this purpose or by editing the text in which the parameter name is defined. It is also possible to create an entity called a cell which is stored separately from the design file. Copies of the cell can be placed in any design and the parameters can be edited both during and after placement.

3. Adding a coupler point

Once the basic underlying mechanism has been modeled, it is relatively easy to add other elements which represent an extended link. This can be illustrated by adding a third point on the coupler and using the system to trace out the path followed by this coupler point.

The outline of the coupler link may be sketched using lines. Two lines can be added to form a triangle whose base is the coupler link. It is convenient for visualization to connect these lines to the ends of the coupler but it is not necessary. Their function in the model is to define a constraint point at their intersection.

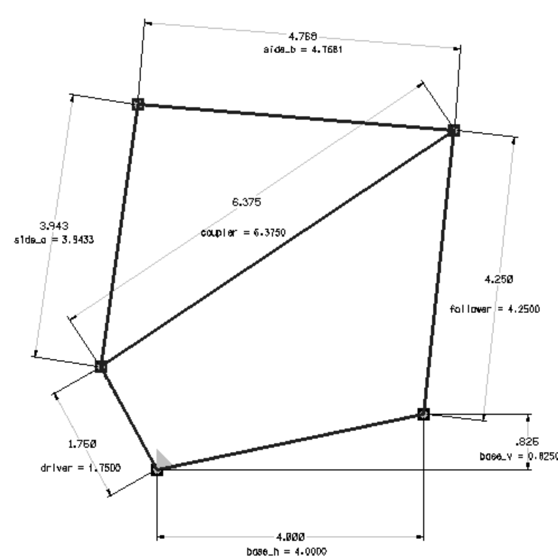

Figure 4. The original 4-bar linkage with a coupler point added.

A constraint point at the intersection of the two new lines will become the desired coupler point. It is important not to create any other constraint points, since the other two points which define the triangle already exist.

Graphic elements can now be attached to represent the coupler. Again, we can use a line string or polygon (triangle here) whose vertices are attached to the three constraint points.

The shape of the coupler link is then fixed by dimensioning the two new sides of the coupler. Again be sure to dimension either the new attached geometry or the distance between the points. The final result should look something like Figure 4. Some designers prefer to locate the coupler point in terms of a distance and the angle between a line and the line of the coupler. This can be done by creating a constraint dimension for the angle between the two lines.

It is very useful to generate the path followed by the coupler point as part of the analysis of the mechanism. Many mechanism design problems can be stated in terms of producing the desired motion of a point such as the coupler point we have just created. This is done in MicroStation by attaching what is called a *Pen Element* to the point. A small circle was used as the pen element in the example shown in Figure 5. As the mechanism moves, it will leave a trail of copies of itself to trace out the path which it follows. This path is the coupler path for this point. The graphics created by the pen element is temporary and will disappear at the first screen update.

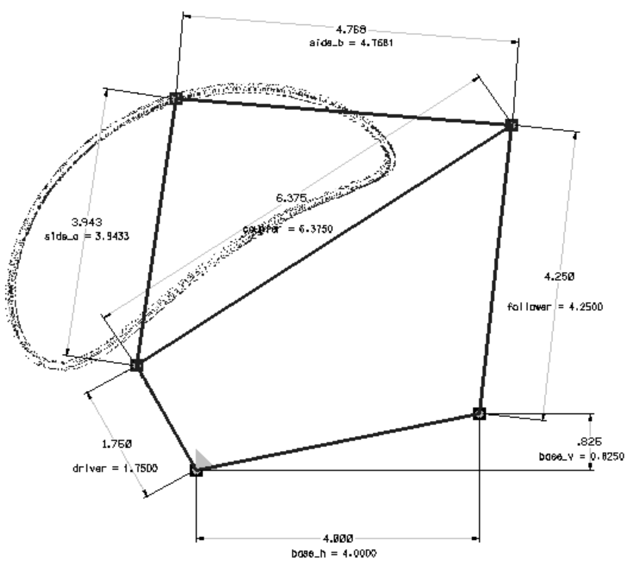

Figure 5. Tracing the path of the coupler point.

4. Adding Links to an Existing Mechanism

The techniques described above can be used to add links to an existing mechanism to produce a linkage of any desired complexity. The designer should plan these additions in a way which gives the maximum possible flexibility. For example, if additional ground points are needed it is very tempting to simply constrain them to have a fixed location. However, using dimensions to constrain their location relative to a single fixed point gives the designer much more flexibility to modify the design. The designer must exercise some care in applying constraints so that the system does not become over-constrained.

5. Other types of joints

The joints we have defined so far represent pin or revolute joints. The are one degree of freedom joints since they allow only relative rotation between the two links which they connect. Many common and useful mechanisms are made entirely with revolute joints. The next most common type of joint is the equivalent of a pin riding in a slot (either straight or curved). This is called a two degree of freedom joint since it allows both rotation and

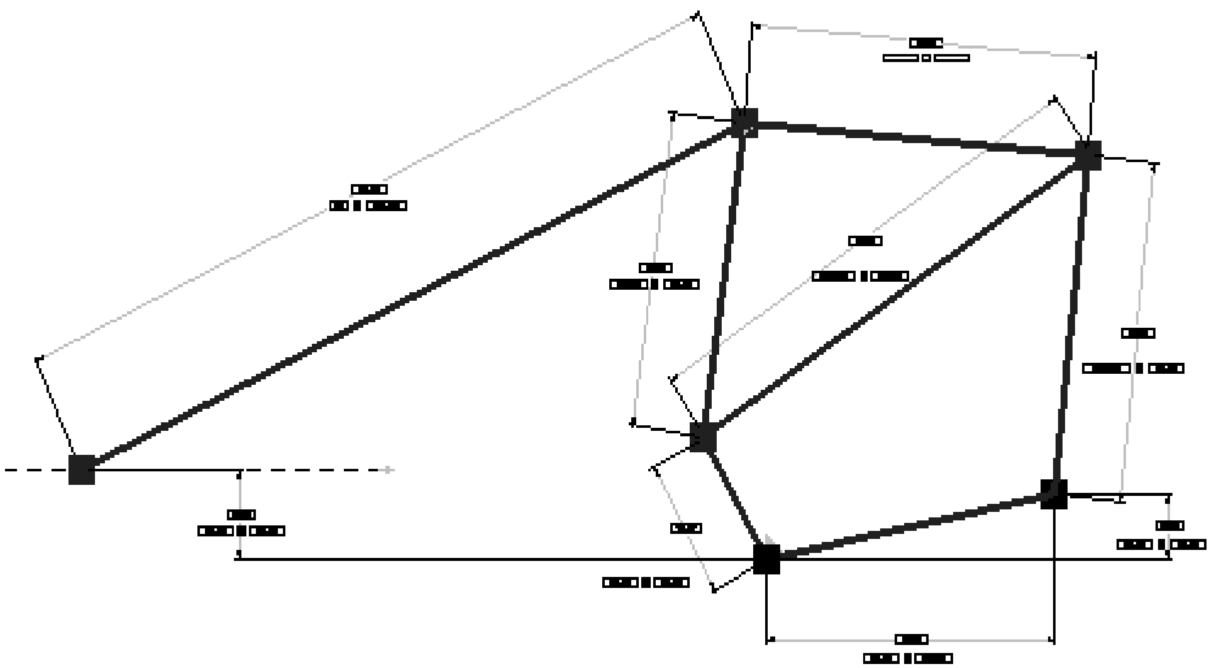

Figure 6. A Stephenson six-bar mechanism (inversion III) with a sliding joint at the left.

translation between the two links. This type of joint can be modeled by using intersection points as well. An element is placed to represent the path along which the pin slides. The location of this element is constrained and then the intersection point is allowed to slide along this path. A six-bar linkage with such a joint is shown in figure 6.

6. Standard Synthesis Techniques

It is possible to integrate the techniques described here into many of the standard graphical synthesis techniques[2]. An example of a three position synthesis with specified fixed pivots is shown in figure 7. In this mechanism, the design problem is to design a mechanism to move an output bar through three specified positions in sequence, with the constraint that the location of the fixed pivots is specified.

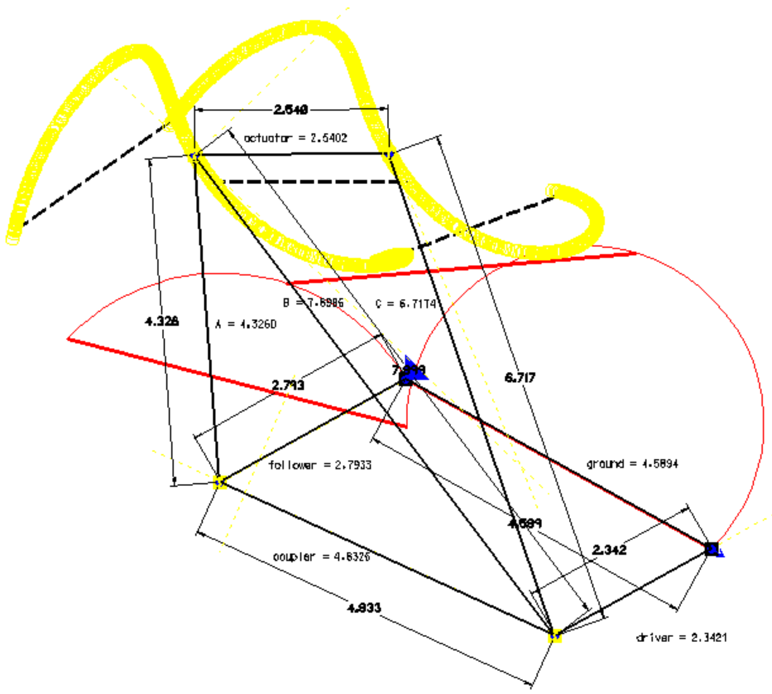

Figure 7. Three position synthesis with fixed ground points. The figure shows the geometric construction and the model of the resulting mechanism. The three dashed lines represent the desired output positions. The paths followed by the output bars are also shown.

7. Summary

Constraint-based techniques developed for other applications have proven to be useful in the synthesis and analysis of linkages. The examples shown in this paper illustrate their use in position synthesis and analysis. A further direct application in this applications is the location of instantaneous centers of velocity since these positions can be defined in terms of intersections based on Kennedy's theorem. It is also relatively easy to extend these techniques to velocity and acceleration analysis by constructing the velocity and acceleration polygons. These can be very helpful to the designer in visualizing the behavior of a mechanism. Some care is required to insure correct directions since dimension parameters are intrinsically scalar in nature. Constructions based on instant centers are generally most useful in this regard. It is also possible to construct mathematical relationships (equalities and inequalities) involving constraint parameters. Inequalities can be used to model physical stops which limit the motion of elements in the mechanism.

The software used in our course is the same as that used in our Engineering Graphics courses. Students with reasonable familiarity with the CAD software usually are able to pick up these techniques fairly quickly. Even transfer students whose graphics experience is in other software packages can usually make the transition fairly quickly because the drawing tools involved are quite simple (mostly drawing lines and arcs). I also provide the students with fairly detailed written instructions for applying the particular tools in MicroStation. For example, they are given a step-by-step, keystroke specific, set of instructions for constructing the linkages shown in figures 1-6 before they are assigned any other problems. I think that these techniques provide both practical design tools and useful insights into the behavior of a variety of mechanisms.

Bibliography

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