Forming a Strong Association Between Dimensional Data in Sketches and Engineering Drawings

Dr. Oziel Rios, University of Texas at Dallas

Dr. Oziel Rios earned his Ph.D. in mechanical engineering from the University of Texas at Austin in 2008 where his research focused on design of robotic systems with an emphasis on kinematic and dynamic modeling for analysis and control. Dr. Rios teaches the first-year and CAD courses in the Mechanical Engineering Department at the University of Texas at Dallas. Dr. Rios has also taught kinematics and dynamics of machines and graduate-level CAD courses. Dr. Rios' research and teaching interests include: robotics, design, kinematics and dynamics of machines and engineering education.

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Abstract

Two-Dimensional (2D) computer-based sketches are fundamental to generate 3D models in many of the Computer-Aided Design (CAD) software applications implemented in engineering graphics and design courses. Furthermore, engineering drawings rely on these 3D models to document and communicate designs. Although much of the dimensional data included in engineering drawings comes from the model's sketches, students sometimes struggle forming a connection between these resulting in drawings that are either under-dimensioned or over-dimensioned. In this evidence-based practice paper, an instructional method to teach the interaction between sketch curves, constraints, and dimensions is presented with the goal of creating engineering drawings with suitable dimensional data. Exercises that have been developed and refined are presented to illustrate the method and convey best-practice approaches in the classroom. Examples of student work is presented to illustrate the common mistakes made. The method presented is independent of the CAD software and can be taught in first-year graphics courses or even upper-level design courses.

1. Introduction

When starting to learn a CAD software, students may focus on the mechanics of using the software (e.g., clicks of the mouse needed to create a line or a circle) but they may not be fostering an understanding of the number and types of dimensions needed to define the shapes they are generating and how these dimensions are affected by their choice of constraints. Eventually, students will be required to create engineering drawings of the 3D models following the standards of ASME [1-2], or the like, and any additional rules set by their instructors. When creating an engineering drawing, it is imperative that only the necessary dimensional data be provided. Providing more dimensional data than necessary or omitting data will cause confusion when manufacturing the component. Figure 1 illustrates the differences between the dimensions and constraints in a sketch representing the cross-section of a 3D model and an example of how the same cross-section might be dimensioned in an engineering drawing.

Sketches are fundamental to mechanical component design because they can be mapped to the manufacturing operations used to fabricate the components. In this work, a sketch is a 2D, planar geometric model comprised of [3-6]:

- 2D curves such as line segments, circles, and circular arcs;
- references to locate the curves on the sketch plane (e.g., coordinate axes);

- dimensional constraints (or simply dimensions) to specify the size, location, and orientation of the curves;

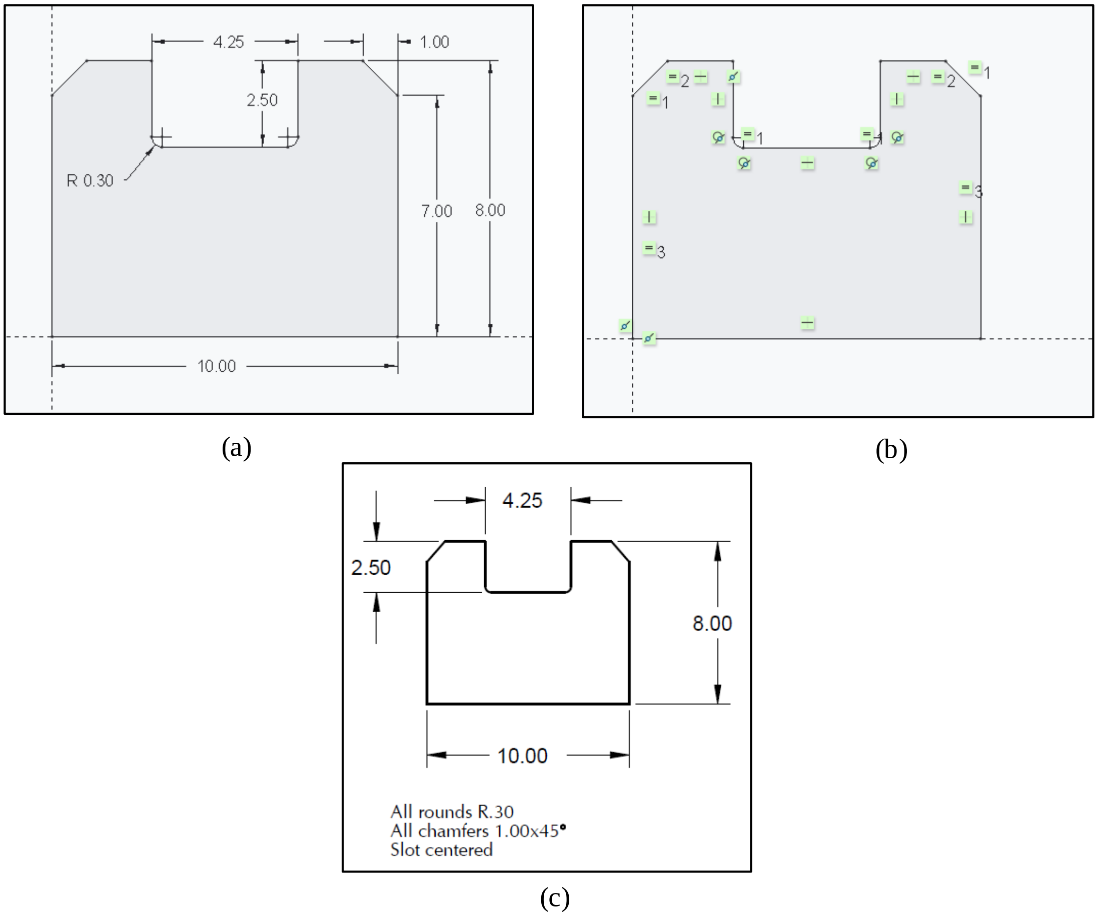


Figure 1. Illustration of (a) sketch dimensions, (b) sketch constraints, and (c) engineering drawing dimensions and notes. Sketch and drawing created in CREO Parametric™ version 6.

- geometric constraints to create relationships between the curves (e.g., make two line segments equal in size and parallel);
- and, associative constraints to create relationships between dimensional constraints.

Figure 1a shows an example of a sketch with dimensions and Figure 1b shows the geometric constraints. The way in which curves are used and how dimensions and geometric constraints are established between them gives purpose to the sketch. This purpose is referred to as design intent and at the sketch level it refers to the intelligent arrangement of curves, references, dimensions, and the application of constraints [3]. Associative constraints are mathematical expressions relating dimensional constraints through the use of arithmetic functions, trigonometric functions, and conditional expressions [6]. The application of associative

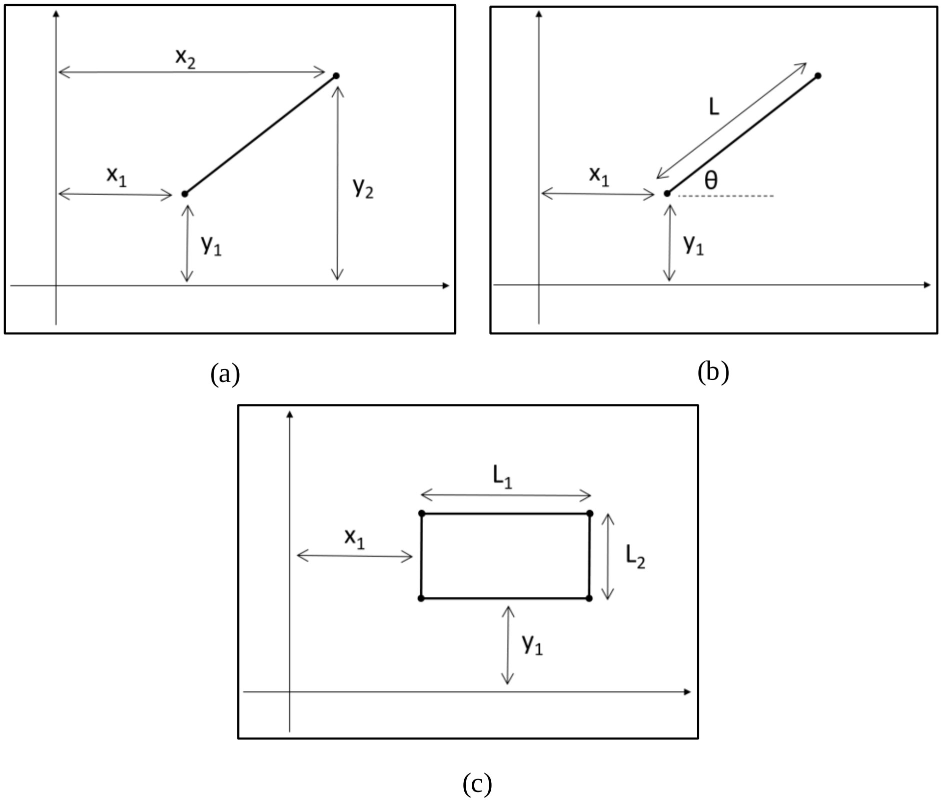


Figure 2. Representations of (a,b) a line segment and (c) a rectangle.

constraints ensure models are robust and satisfy design intent when changes to the dimensions are made especially when someone other than the original designer makes the changes. In this work, the relationship between curves, dimensions and geometric constraints will be addressed.

The goal of this work is to provide a method students can implement to form a strong association with the geometry of models and the necessary dimensional data needed to define them. Section 2 will provide a method to determine the number of dimensions needed for a sketch while Section 3 will provide exercises that have been developed and implemented. Examples of student work is presented in Section 4. Section 5 is reserved for conclusions.

2. Analysis of Sketch DOF

Sketch constraints are essential to capturing design intent in the models we create. Adding constraints to a sketch reduces the number of dimensions you have to specify. As an example, consider drawing a general line segment. A general line requires 4 dimensions to specify its size and location on the sketch plane. In one representation, two end-points could be specified (see Figure 2a) while in another one end-point, it's length, and the angle formed relative to the horizontal axis could be specified (see Figure 2b). Regardless of the type of dimensions used to specify the line segment, four dimensions would still be required. If the line segment would be constrained to be horizontal, the number of dimensions would be reduced to three because the y-coordinates of the end-points would be equal (i.e., $y_1 = y_2$ in Figure 2a or $\theta = 0°$ in Figure 2b).

Next, consider a rectangle with no rotation as shown in Figure 2c. Clearly, this shape would require four dimensions to specify its size and location – two size dimensions and two location dimensions. The rectangle is composed of four line segments and several types of constraints including coincidence points (the point where two line segments are joined), horizontal line constraints, and vertical line constraints. This combination of lines and constraints produces the rectangular shape.

The number of parameters needed to define a curve and the number of parameters eliminated through the application of constraints are used to determine the number of dimensions for a sketch. The number of independent parameters needed to define a curve are called degrees-of-freedom (DOF). Table 1 lists various curve types and the number of parameters needed to define them based on their parametric equations. The instructor can omit the parametric equation when presenting this method to students who have not studied them in their math courses. This will not hinder their learning process. Table 2 shows some common geometric constraints you can apply to your sketches. Note that some constraints are applied to points whereas others are applied to line segments (e.g., 'tangent point' versus 'horizontal line'). In CREO Parametric and SolidWorks, some constraint symbols have a number as a subscript. These constraints occur in sets. For example, three line segments could be made parallel to each other. These three line segments would have the 'parallel lines' constraint with the set number.

While sketching, it is important to remember that a particular shape could be created using different constraint types. For example, the rectangular shape could be created using 'horizontal line' and 'vertical line' constraints but we could also use 'parallel lines' and 'perpendicular lines' or even 'perpendicular point' constraints. If the sketch is offset from the origin of the sketch plane, two location dimensions will be necessary. If the sketch is not related to any other feature, these location dimensions are inconsequential and can be removed though the application of constraints. This is referred to as 'grounding' the sketch. Ground can be achieved through the application of two 'point on a curve' constraints or through the application of two 'symmetric point' constraints. Similarly, the orientation of the sketch may be inconsequential. Removing this orientation dimensions can be achieved using a 'horizontal line' constraint, for example. Refer to Figure 1b for an example of grounding and the removal of the orientation dimensions.

Table 1. 2D sketch curves with their associated DOF value.

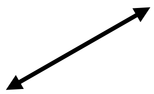
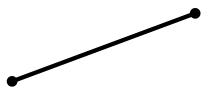
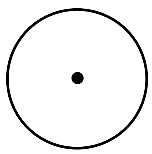
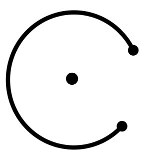
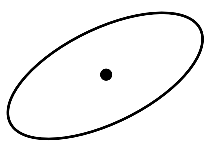
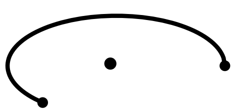
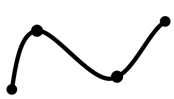
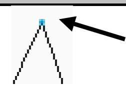
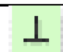
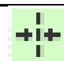
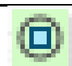
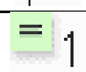
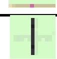
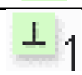
Curve	Diagram	DOF	Sample Parameters	Parametric Equation
Point		2	(x,y) coordinates	-
Line (Centerline)		3	Coordinates of a point on the line (x_1, y_1) and orientation θ	$x = x_1 + \cos(\theta)\, t$ $y = y_1 + \sin(\theta)\, t$ $t \in [-\infty, \infty]$
Line Segment		4	Coordinates of end-points (x_1, y_1) and (x_2, y_2)	$x = x_1 + (x_2 - x_1)t$ $y = y_1 + (y_2 - y_1)t$ $t \in [0,1]$
Circle		3	Coordinates of center point (x_c, y_c), diameter D	$x = x_c + \frac{D}{2}\cos(t)$ $y = y_c + \frac{D}{2}\sin(t)$ $t \in [0,2\pi]$
Circular Arc		5	Coordinates of center point (x_c, y_c), start angle θ_0, interior angle $\Delta\theta$, radius R	$x = x_c + R\cos(\theta_0 + \Delta\theta t)$ $y = y_c + R\sin(\theta_0 + \Delta\theta t)$ $t \in [0,1]$
Ellipse		5	Coordinates of center point (x_c, y_c), major diameter D_1, minor diameter D_2, orientation ϕ	$x = x_c + \frac{D_1}{2}\cos(t)\cos(\phi) - \frac{D_2}{2}\sin(t)\sin(\phi)$ $y = y_c + \frac{D_1}{2}\cos(t)\sin(\phi) + \frac{D_2}{2}\sin(t)\cos(\phi)$ $t \in [0,2\pi]$
Elliptical Arc		7	Coordinates of center point (x_c, y_c), major diameter D_1, minor diameter D_2, start angle θ_0, interior angle $\Delta\theta$, orientation ϕ	$x = x_c + \frac{D_1}{2}\cos(\theta_0 + \Delta\theta t)\cos(\phi) - \frac{D_2}{2}\sin(\theta_0 + \Delta\theta t)\sin(\phi)$ $y = y_c + \frac{D_1}{2}\cos(\theta_0 + \Delta\theta t)\sin(\phi) + \frac{D_2}{2}\sin(\theta_0 + \Delta\theta t)\cos(\phi)$ $t \in [0,1]$
Spline		2N	Coordinates of each of the N points: $(x_1, y_1) \ldots (x_N, y_N)$	$x = a_{N-1}t^{N-1} + \cdots + a_1 t + a_0$ $y = b_{N-1}t^{N-1} + \cdots + b_1 t + b_0$ $t \in [0,1]$ Need to compute coefficients a_i and b_i based on coordinates

Table 2. The DOF removed by typical geometric constraints. The symbols provided are implemented in CREO Parametric™ version 6 but similar symbols are used in other CAD software.

Geometric Constraint	Symbol	DOF Removed	Description
Coincidence Point		2	End-points of two curves at same location
Tangency Point		1	Smooth transition between two curves with coincident end-points
Perpendicular Point		1	90 degrees between two curves at coincident end-points
Point on a Curve		1	Point constrained to lie on a curve
Symmetric Points		1	Equal distance between two points and a centerline
Concentric Points		2	Center points of two circles or arcs have same location
Horizontal Point Alignment		1	Two curve end-points have same vertical location
Vertical Point Alignment		1	Two curve end-points have same horizontal location
Equal Size		1	Size of two curves are equal (equal lengths or equal radii)
Horizontal Line		1	Line or line segment made horizontal
Vertical Line		1	Line or line segment made vertical
Perpendicular Lines		1	Two lines or line segments are at 90 degrees to each other
Parallel Lines		1	Two lines or line segments have same slope

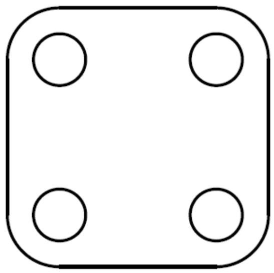
3. Exercises

Tables 1 and 2 will be used to determine the number of dimensions needed for a cross-section as it would appear in an engineering drawing. Since constraints are not shown in drawings, the student must first make notable observations about the shape. These observations are then translated into the DOF of curves as in Table 1 and DOF removed by constraints as in Table 2. Three exercises illustrating this procedure are shown in Figures 3, 5, and 7. The goal of these exercises is to observe and understand how constraints affect the number of dimensions. With practice, students will develop an intuition about how to dimension engineering drawings. At that point, they would no longer resort to this method.

3.1 Exercise 1

The shape of Exercise 1 (see Figure 3) is a square with rounded corners and four holes. Observation #1 would be the most obvious when we first see this shape. This observation would be translated into Constraints #1 – namely, that the two sets of opposite lines are parallel, two adjacent lines are perpendicular, and two adjacent lines are equal in length. The next observations would be that the circles and the corner arcs are equal in size (Observations #2 and #3). This means that three equal size pairs are applied to the circles and another three equal size pairs would be applied to the arcs. Observation #4 is critical because there are no gaps between the arcs and line segments and there are smooth transitions between them. It would also be observed that the circles and arcs share the same center points (Observation #5). Finally, since the sketch is not related to another shape, its location and orientation would be inconsequential to its manufacture (Observations #6 and #7) and, therefore, these dimensions would not be needed. Figure 3 shows how the observations (Step 0) would be converted into the total DOF of the curves (Step 1) and into the total DOF removed by the constraints (Step 2). The number of dimensions would be determined by subtracting the results of the previous steps (Step 3). The constraint list in Step 2 is used to determine the effects of making modifications to the shape. For example, if the shape was rectangular instead of a square, the equal length constraint would be eliminated increasing the number of dimensions to 4. Finally, Figure 4 shows the sketch with dimensions and constraints.

An important note to make to the students as the exercise is worked on in a classroom setting is to not specify more than the necessary constraints. In Exercise 1, a novice student might make Observation #1 and want to add 2 'equal size' pairs instead of only one. Namely, the student may want to make adjacent lines equal in size (correct) but may also want to make opposite lines equal in size which would be incorrect as this equality would already be implied due to the application of 'parallel line' and 'perpendicular line' constraints.



<u>Step 0</u>: *<u>Observations</u>*

1. Shape is a square (opposite sides are parallel, adjacent sides are perpendicular, and side lengths are equal in size).
2. Four circles are equal in size.
3. Four corner arcs are equal in size.
4. Smooth transition between arcs and line segments.
5. Circles and arcs are concentric.
6. Cross-section location is inconsequential.
7. Cross-section rotation is inconsequential.

<u>Step 1</u>: *<u>DOF of Curves</u>*:

1. 4 Line Segments = 16 DOF
2. 4 Circles = 12 DOF
3. 4 Arcs = 20 DOF

TOTAL = 48 DOF

<u>Step 2</u>: *<u>DOF Removed by Constraints</u>*:

1. 2 Parallel Line Pairs = 2 DOF
   1 Perpendicular Line Pair = 1 DOF
   1 Equal Size Pair = 1 DOF
2. 3 Equal Size Pairs = 3 DOF
3. 3 Equal Size Pairs = 3 DOF
4. 8 Coincidence Points = 16 DOF
   8 Tangent Points = 8 DOF
5. 4 Concentric Points = 8 DOF
6. Sketch Grounded = 2 DOF
7. 1 Horizontal Line = 1 DOF

TOTAL = 45 DOF

<u>Step 3</u>: *<u>Number of Dimensions Needed</u>*:

48 – 45 = **3 DOF**

Figure 3. DOF analysis of Exercise 1. The observations are numbered and correspond to the constraints applied in Step 2.

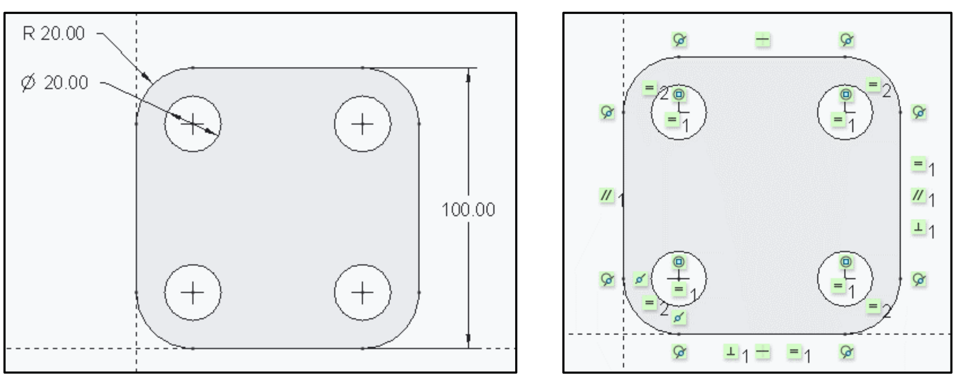
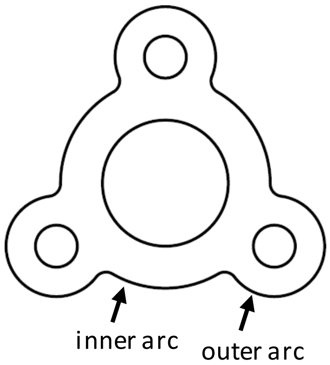


Figure 4. Sketch of Exercise 1 showing dimensions and constraints.

3.2 Exercise 2

Exercise 2 shows a more complex shape. This shape is symmetric about the vertical axis and is composed of only circles and circular arcs. One observation would be that the three small circles are equidistant from the center of the larger circle. The small circles can be thought of as lying on a construction circle. Hence, a construction circle was added in Step 1 and point on curve constraints were added in Step 2 (Constraints #1). For experienced designers, it may be fairly obvious that seven dimensions are needed to define the shape; five dimensions are for curve size – diameters of small and large circles and radii of inner, outer, and fillet arcs – and two dimensions are for the location of curves – the diameter of the construction circle and the angle. This intuition matches the result of the sketch shown in Figure 6. For novice students, however, going through the mechanics of this method will nurture their intuition.



Step 0: *Observations*

1. Three small circles are equal in size, concentric to the three outer arcs, equidistant from large circle center (centers lie on same construction circle), and the centers of the two lower circles are aligned.
2. Three outer arcs are equal in size.
3. Three inner arcs are equal in size and concentric to large circle.
4. All fillets are same size.
5. Smooth transition between arcs.
6. Cross-section location is inconsequential.
7. Cross-section rotation is inconsequential (upper circle lies on vertical axis).

Step 1: *DOF of Curves*

1. 4 Circles = 12 DOF
2. 1 Construction Circle = 3 DOF
3. 12 Arcs = 60 DOF

TOTAL = 75 DOF

Step 2: *DOF Removed by Constraints*

1. 2 Equal Size Pairs = 2 DOF
   4 Concentric Points = 8 DOF
   3 Point on Curve = 3 DOF
   1 Symmetric Point = 1 DOF
2. 2 Equal Size Pairs = 2 DOF
3. 2 Equal Size Pairs = 2 DOF
   3 Concentric Points = 6 DOF
4. 5 Equal Size Pairs = 5 DOF
5. 12 Coincidence Points = 24 DOF
   12 Tangent Points = 12 DOF
6. Sketch Grounded = 2 DOF
7. 1 Point on Curve = 1 DOF

TOTAL = 68 DOF

Step 3: *Number of Dimensions Needed*

75 – 68 = **7 DOF**

Figure 5. DOF analysis of Exercise 2. The observations are numbered and correspond to the constraints applied in Step 2.

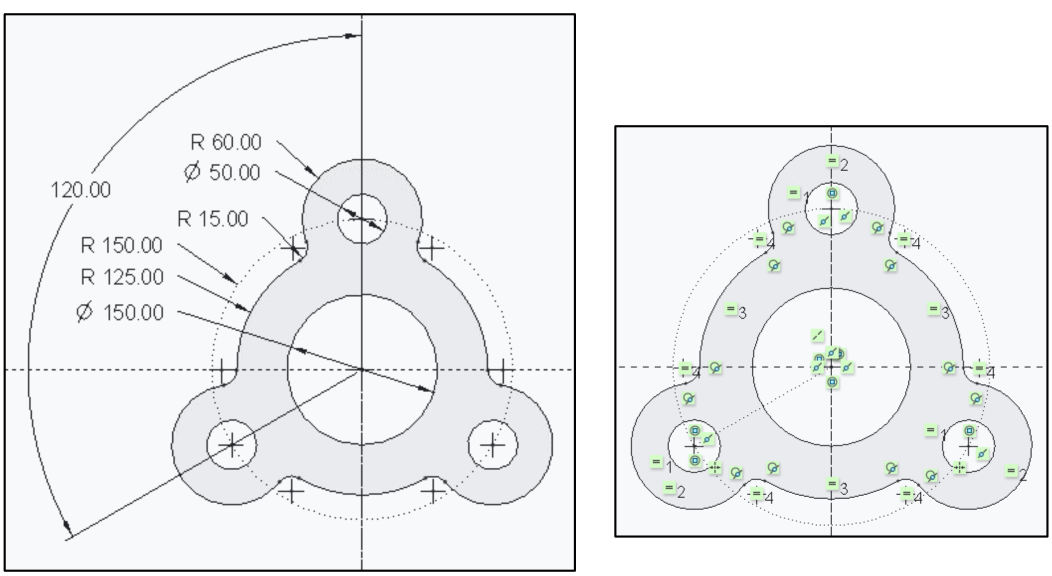
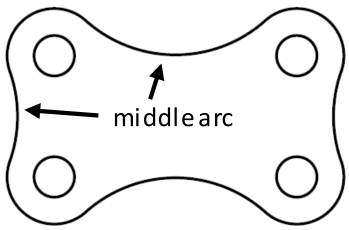


Figure 6. Sketch of Exercise 2 showing dimensions and constraints.

3.3 Exercise 3

Exercise 3 is shown in Figure 7. This shape would require five dimensions - the diameter of the circles, the radius of the corner arcs, the radius of the middle arcs, as well as the horizontal and vertical distances between the circle centers. The sketch with dimensions and constraints are shown in Figure 8.



Step 0: *Observations*

1. Four circles are equal in size.
2. Four corner arcs are equal in size and concentric to circles.
3. Smooth transition between arcs.
4. Middle arcs are equal in size and open horizontally or vertically.
5. Cross-section location and rotation are inconsequential (align centers of circles horizontally and vertically).

Step 1: *DOF of Curves*

1. 4 Circles = 12 DOF
2. 8 Arcs = 40 DOF

TOTAL = 52 DOF

Step 2: *DOF Removed by Constraints*

1. 3 Equal Size Pairs = 3 DOF
2. 3 Equal Size Pairs = 3 DOF
   4 Concentric Points = 8 DOF
3. 8 Coincidence Points = 16 DOF
   8 Tangent Points = 8 DOF
4. 3 Equal Size Pairs = 3 DOF
   4 Point on Curve = 4 DOF
5. 2 Alignment Points = 2 DOF

TOTAL = 47 DOF

Step 3: *Number of Dimensions Needed*

52 – 47 = **5 DOF**

Figure 7. DOF analysis of Exercise 3. The observations are numbered and correspond to the constraints applied in Step 2.

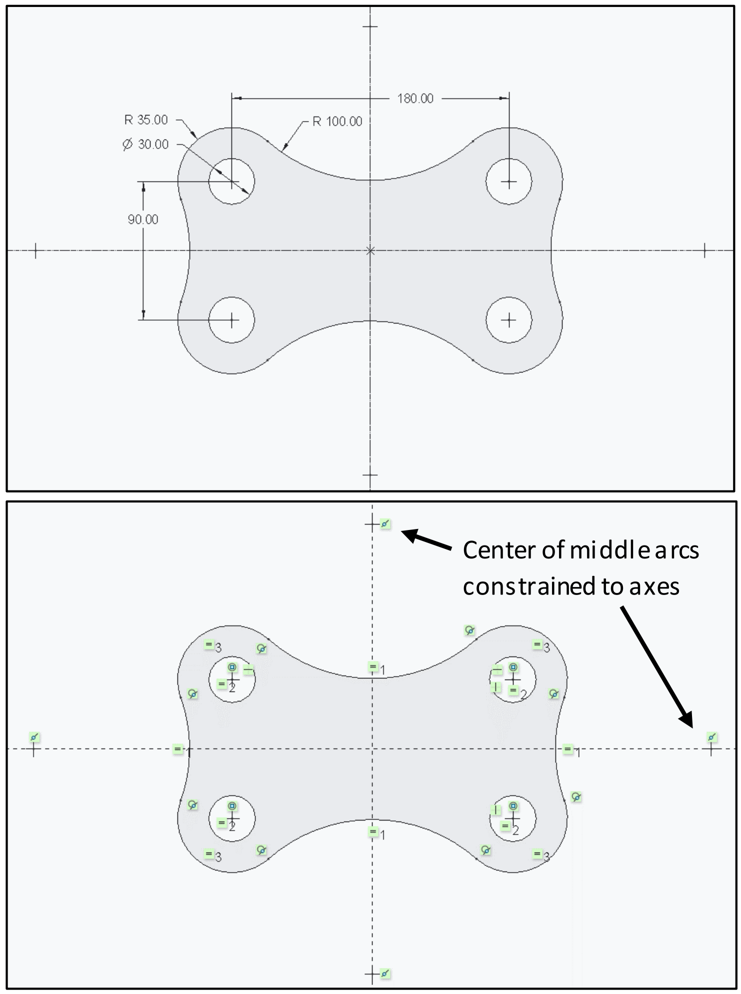


Figure 8. Sketch of Exercise 3 showing dimensions and constraints.

4. Examples of Student Work

In the previous section, three exercises that can be used to demonstrate the approach in a classroom setting were provided. In the Fall 2019 semester, Exercises 1 and 2 were discussed with students in a face-to-face lecture and Exercise 3 was left for students to work as a take-home exercise. An analysis of the student's work is presented here.

Figure 9 shows an example of student work where the student arrived at the correct answer. The majority of the constraints applied by the student follow those in Exercise 3 (see Figure 7); however, the student applied horizontal and vertical alignment points and symmetry points instead of the point on line constraints (see Figure 8). The student even provided the dimensions needed to specify the cross-section's size.

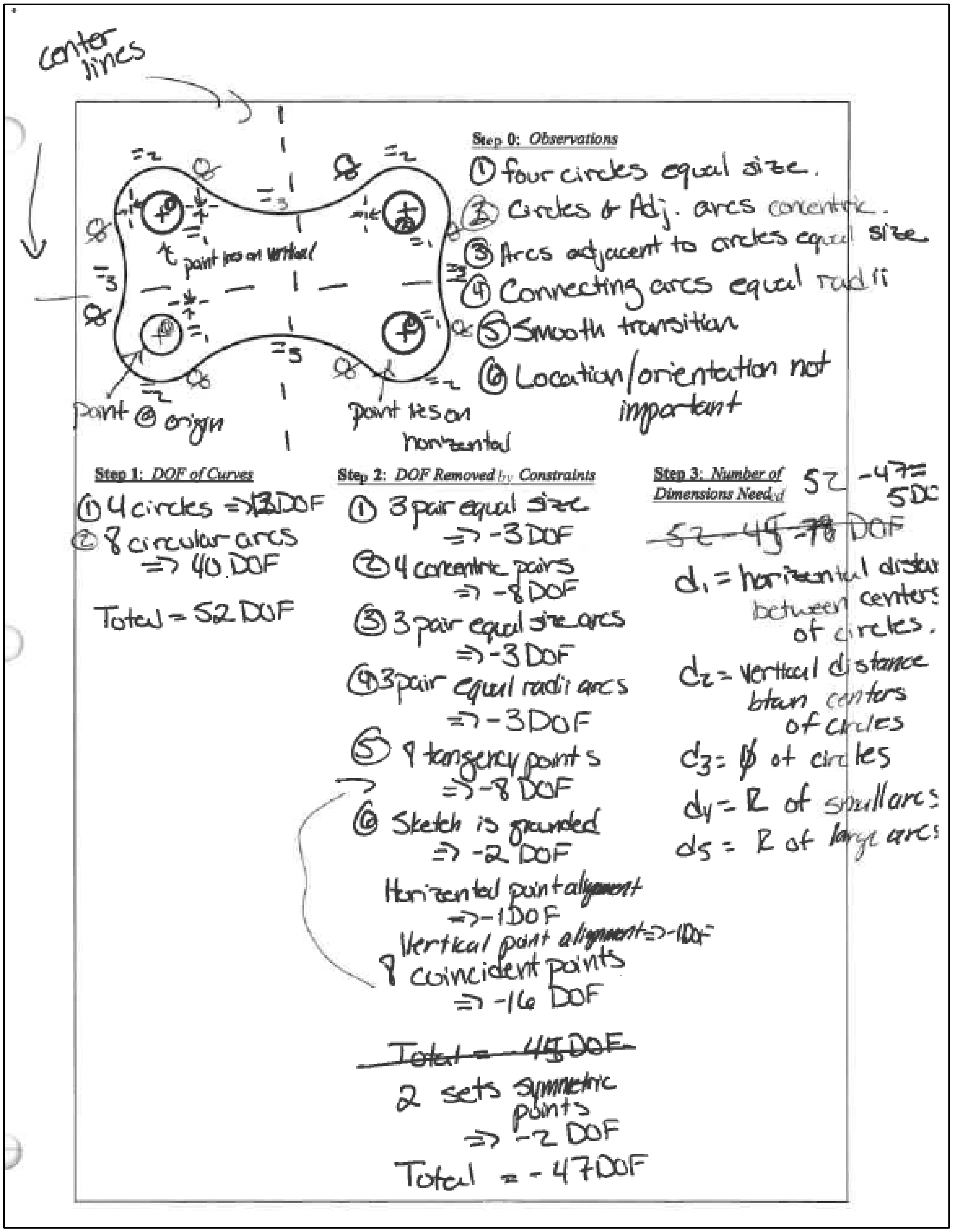


Figure 9. Sample of student work for Example 3 where the student arrived at a correct answer.

Figure 10 shows an example of student work where the student arrived at an incorrect answer. This student was also able to identify a majority of the constraints but this student did not apply the constraints necessary to make the cross-section symmetric. This resulted in an additional four dimensions.

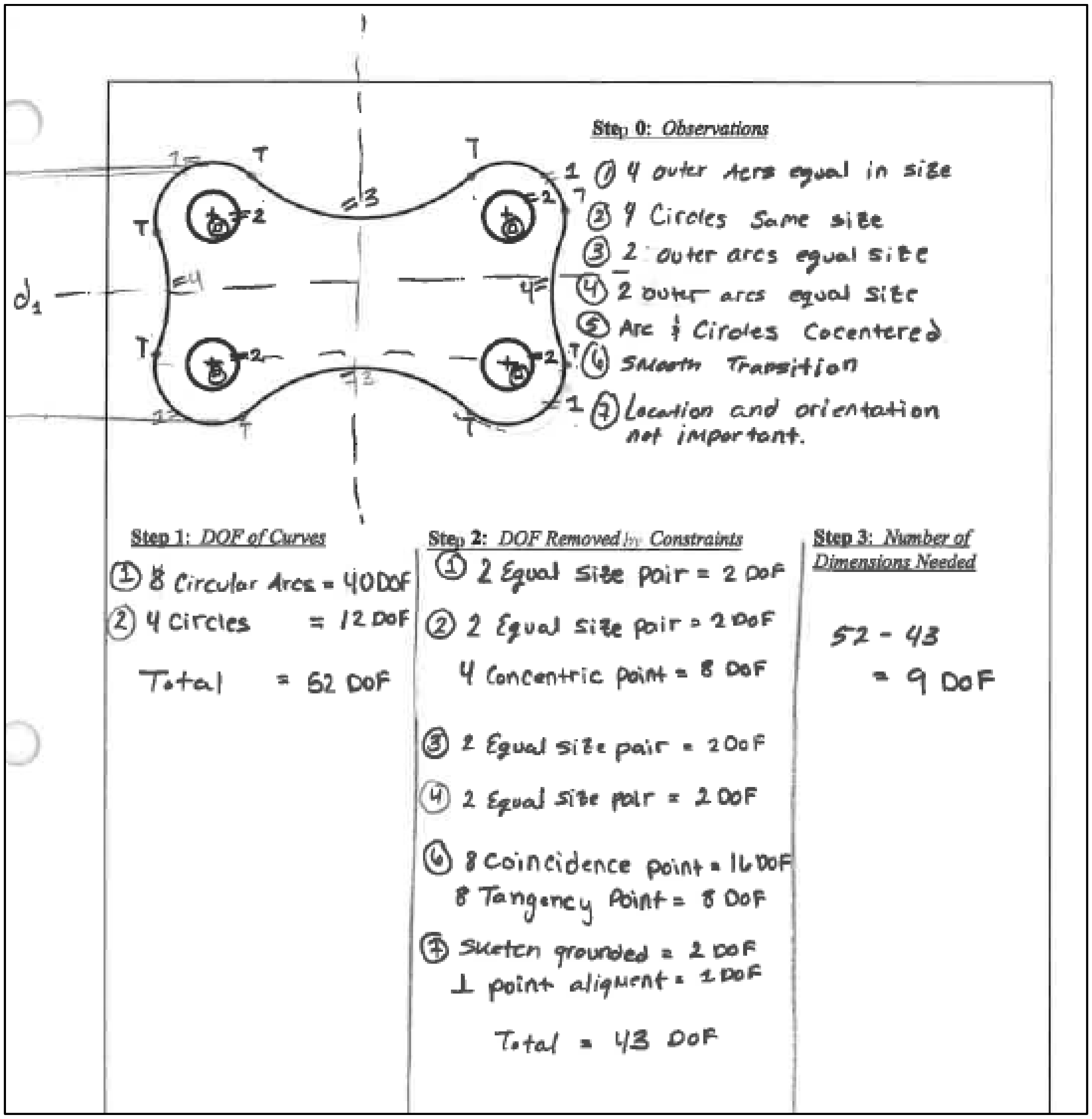


Figure 10. Sample of student work for Example 3 where the student arrived at an incorrect answer.

Twenty-nine (29) students participated in the exercise in a class of 36. This exercise was not for credit and students were given two days to complete it. An analysis of the student submissions resulted in the following observations.

- 18 students determined the number of dimensions correctly. These students made appropriate observations about the shape and determined the DOF in each step correctly following these observations.

- 6 students made a mistake in Step 1. The mistakes made by the students were as follows. One student used 4DOF per circle instead of 3DOF. One student miscounted the number of arcs but had the correct DOF per circle and arc. One student had the incorrect DOF per circle and arc. One student was creative in how to make the cross-section symmetric using a "construction rectangle" but failed to add the correct DOF. Interestingly, one student interpreted the 4 middle arcs as 3-point splines but otherwise followed a correct procedure. One simply made a math error.
- 10 students made a mistake in Step 2. The mistakes made were as follows. 7 students incorrectly applied or missed the symmetry constraints to make the cross-section symmetric about the horizontal and vertical axes (see Figure 8) leading to 2-4 extra dimensions depending on the constraints they applied. In the solution presented in Figure 7, symmetry is achieved by applying 4 'point on curve' constraints so the middle arcs open horizontally or vertically. 3 students had an abundance of dimensions due to missing coincident point constraints (2 of these students also made mistakes with symmetry). 2 students over constrained the cross-section resulting in less than 5 dimensions.
- No students made math errors in Step 3.

Interestingly, only a minority of students applied redundant constraints (only 2 out of 29 made this mistake). It was more likely that students lacked constraints to get the correct shape due to the variety of ways this can be achieved. In this case, the main issue was ensuring symmetry. Finally, there was substantial overlap between making a mistake in Steps 1 and 2. Since these students interpreted the curves incorrectly or miscounted the total curve DOF, they could have misjudged the shape obtained through the application of constraints leading to them to overlook symmetry.

5. Conclusions

In this paper, an instructional method to teach the interaction between sketch curves, geometric constraints, and dimensions is presented. This method relies on the DOF of 2D curves and geometric constraints to determine the number of dimensions needed to fully define a sketch. Exercises are provided to illustrate the method. In these exercises, cross-sections that are found in engineering drawings are given to the students so they can make observations about the geometry. These observations are then converted into curve elements and sketch constraints and the number of dimensions are computed. Examples of student work is presented to illustrate common mistakes made by students. It was observed that students are more likely to under-constrain a cross-section leading to extra dimensions. The method presented here is independent of the CAD software implemented and can be taught to first year students or even to upper-level students.

6. References

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