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CONTRACT REPORT

PLACEMENT AND PACKAGING OF
TWO-DIMENSIONAL OBJECTS ON
A PANEL (FINAL REPORT)

Prepared by

E. W. Whitaker

Thomas Bede Foundation

SANDIA LABORATORIES

OPERATED FOR THE U. S. ATOMIC ENERGY COMMISSION BY SANDIA CORPORATION

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(Final Report)

Prepared by

E. W. Whitaker

Thomas Bede Foundation
745 Distel Drive
Los Altos, California

for

Sandia Laboratories

under

Contract 47-0102

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PLACEMENT AND PACKAGING OF TWO-DIMENSIONAL OBJECTS ON A PANEL

Description of Problem

Given a panel or a bulkhead of a configuration described by two circles as in Figure 1, arrange and place objects so that they are wholly contained on the panel and do not overlap each other. They should be placed and oriented (rotated) for minimum unused space, yet allow for specific or preferred placement and orientation for certain objects. Also, it may be required that some objects be grouped together and others be dispersed.

Produce drawings, plots, and lists of the data.

TYPICAL PANEL

Figure 1

Method of Solution

The procedure is an iterative simulation of a small unreal universe filled with objects, and subject to "forces" and "constraints" that suit our needs.

The system of "objects" and "forces" is processed until it has "run down" (no movement or interaction occurs between objects or the boundary) and the placement and orientation of the objects meets chosen criteria.

A proper selection of forces is the most important part of the procedure. In nature we find typical examples of forces, but not necessarily the best forces for our purposes. In fact some forces, such as inertia, are harmful to our placements. For our problem, we have invented our own forces as we needed them.

Our criteria state that all objects will be contained on the panel, so we represent the panel as a boundary with a force of repulsion to keep objects inside the boundary. The criteria also state that objects may not overlap each other, so a force of repulsion is given to all objects.

Some objects may need to be placed in specific areas or at specific points, and some objects need to be grouped together or kept far apart. These objects are given forces of attraction or repulsion as needed. However, if an object needs to go to a specific point, and has other objects in its path, the force of repulsion between objects will prevent it from getting there. To avoid this "trapping" problem, we do not apply the force of repulsion between objects until after the objects get to where their attraction forces take them.

To get "better packing" and to "fill" small or narrow areas, we create a "tilt" force that allows objects to "slide" or "fall" in the direction of the narrow area. After the area is filled, we apply the force of repulsion between objects, so that they will not overlap.

As the forces are applied to an object, we calculate the "torque" on the object about its center, which is used to rotate the object for a "better fit."

Procedure

Because of the ease of computation, all objects are enclosed by one or more circles. All the circles of an object are then subject to the set of computations

determining the forces. The object is then rotated and translated on the basis of these forces. This procedure is continued for each object, until all objects have been processed; then the procedure is repeated.

The first force to be computed is the boundary force. As in Figure 2, let:

X_{BO}, Y_{BO} = center coordinates of the boundary outer circle

R_{BO} = radius of the boundary outer circle

X_C, Y_C = center coordinates of an object represented by a circle

R_C = radius of this circle.

Then the distance (D) from the center of the boundary outer circle to the center of the object circle is:

$$D = \left[(X_{BO} - X_C)^2 + (Y_{BO} - Y_C)^2 \right]^{\frac{1}{2}}$$

If the difference of the radius $R_{BO} - R_C$ is less than distance (D), the circle passes beyond the boundary.

$X_{BO} - X_C$ and $Y_{BO} - Y_C$

Figure 2

provides the X and Y directional components and the component ratio for moving the object.

To compute the boundary inner circle "force," as in Figure 3:

X_{BI}, Y_{BI} = center of boundary inner circle

R_{BI} = radius of boundary inner circle

X_C, Y_C = center of an object represented by a circle

R_C = radius of this circle.

Figure 3

The distance (D) from the point X_{BI}, Y_{BI} to the point X_C, Y_C is:

$$D = \left[(X_C - X_{BI})^2 + (Y_C - Y_{BI})^2 \right]^{\frac{1}{2}} .$$

If distance (D) is less than the sum of the radii

$$R_C + R_{BI}$$

then the object is not wholly contained on the panel, and the ratio of X and Y directional components of the boundary "force" are:

$$X_C - X_{BI} \text{ and } Y_C - Y_{BI}.$$

The force of overlap between circles of two different objects, as in Figure 4, is computed by the same method.

Let

$$X_1, Y_1 = \text{center of circle of object 1}$$

$$R_1 = \text{radius of this circle}$$

$$X_2, Y_2 = \text{center of circle of object 2}$$

$$R_2 = \text{radius of this circle.}$$

Figure 4

Distance (D) between centers of the circles is:

$$D = \left[(X_1 - X_2)^2 + (Y_1 - Y_2)^2 \right]^{\frac{1}{2}}.$$

If the sum of the radii

$$R_1 + R_2$$

is greater than distance (D), object 1 and object 2 overlap, and the direction is computed from:

$$Y_1 - X_2 \text{ and } Y_1 - Y_2.$$

The tilt force is simply a constant subtracted from the Y component of the force acting on an object.

Where:

$$K = \text{constant}$$

$$YF = Y \text{ component of the force}$$

the final force acting on the object is:

$$YF - K.$$

Torque for rotating an object is computed from the sum of the forces acting on all the circles representing that object. See Figure 5.

Where:

$$X_O, Y_O = \text{center of the object}$$

$$X_{C1}, Y_{C1} = \text{center of circle 1 on the object}$$

$$X_{C2}, Y_{C2} = \text{center of circle 2 on the object}$$

$$XF_1, YF_1 = X \text{ and } Y \text{ force on circle 1}$$

$$XF_2, YF_2 = X \text{ and } Y \text{ force on circle 2}$$

the moments about the center of the object are:

$$\begin{aligned} \text{Torque} = & YF_1(X_{C1} - X_O) - XF_1(Y_{C1} - Y_O) \\ & + YF_2(X_{C2} - X_O) - XF_2(Y_{C2} - Y_O). \end{aligned}$$

Figure 5

The attraction force on an object to a point is proportional to the distance.

Given:

X_P, Y_P = point to which the object is attracted

X_O, Y_O = center of the object

XF, YF = force of attraction

K = constant

then

$$XF = K(X_P - X_O)$$

$$YF = K(Y_P - Y_O)$$

Conclusions

The program took more than one hour to place 500 objects. This may seem like a long time; however, it is bound to be faster than by hand, and the computation time can be decreased by increasing the maximum step size which the objects may move, and reducing the number of iterations.

Since only a few objects are not circles, most objects can be very accurately described. Depending on the desired accuracy of the representation of noncircular objects, more or fewer circles are used to represent such objects.

Some disadvantages of this specific program are that the panel must be described by two circles which may or may not be true, and that the computation time increases by the square of the number of objects.

One may choose from a wide variety of output devices. The best known of these, the Calcomp plotter, is relatively slow, but it is moderately accurate and many plotting programs are available for it. The Gerber plotter is one of the most accurate obtainable, and an excellent plotting package can be supplied by P. W. Plomp, 7624, Sandia Laboratories, Albuquerque.

The movies showing the placing technique of this program were made on the S. C. 4020 Film Recorder, with our own plotting routines. This device is very fast, but accurate to only one part in a thousand.

Since our model is a two-dimensional view of the panel, there is no detail on mounting or other structural characteristics; however, these problems have been considered. The following is a list of programs available for structural engineering.

STRESS	- Control Data Corporation, Data Centers Division
BEAMANAL	- Control Data Corporation, Data Centers Division
PIERANAL	- Control Data Corporation, Data Centers Division
ANGIR	- Control Data Corporation, Data Centers Division

Recommendations

At the time of this report, the author was seriously considering other methods of representing and handling noncircular objects because of higher accuracy and ease of data preparation.

Two very interesting methods of describing complex objects are mentioned in the MAGI technique¹ and Warnocks Algorithm.² These approaches are quite sophisticated and perhaps more complicated than is necessary for our needs.

Our problem is to determine if objects are overlapping, and how much they overlap; and to compute a direction to move, and an amount to rotate. By describing an object by a list of consecutive points and specifying a point inside the object, any condition of overlap can be determined.

To compute whether a circle overlaps a noncircular object, the following technique is possible (see Figure 6).

Figure 6

Given:

X_1, Y_1 = point on a line of noncircular object

X_2, Y_2 = another point on the same line

X_C, Y_C = center of circle to be tested for overlap

R = radius of circle

X_I, Y_I = point on line nearest center of circle

D = distance from this point to center of circle

then

$$A_L = \frac{Y_1 - Y_2}{X_1 - X_2}$$

$$B_L = Y_1 - A_L X_1$$

(we don't really believe in dividing by zero--see the program)

and

$$X_I = \frac{A_L(Y_C - B_L) + X_C}{A_L^2 + 1}$$

$$Y_I = A_L X_I + B_L$$

and

$$D = \left[(X_I - X_C)^2 + (Y_I - Y_C)^2 \right]^{\frac{1}{2}}$$

If D is less than R, the circle overlaps the noncircular object. If the center of the circle is outside the object, the exact amount of X and Y movement for the object is:

$$X_M = \frac{(X_I - X_C)(R - D)}{D}$$

$$Y_M = \frac{(Y_I - Y_C)(R - D)}{D}$$

However, if the center of the circle is inside the object (Figure 7), the amount of movement is:

$$X_M = \frac{(X_C - X_I)(R + D)}{D}$$

$$Y_M = \frac{(Y_C - Y_I)(R + D)}{D}$$

To determine if the center of the circle is inside the object, construct a line between the point specified inside the object and the center of the circle (Figure 8).

Figure 7

Figure 8

Compute all intersections of the lines that are made by the object and the line constructed through the center of the circle and the point specified inside the object.

Let:

X_C, Y_C = center of circle

X_O, Y_O = point specified inside the object

X_1, Y_1 = point defining one end of a line of the object

X_2, Y_2 = point defining other end of the line

X_I, Y_I = point of intersection

$$A_I = \frac{Y_I - Y_C}{X_I - X_C}$$

$$B_I = Y_I - A_I X_I$$

$$A_O = \frac{Y_1 - Y_2}{X_1 - X_2}$$

$$B_O = Y_1 - A_O X_1$$

$$X_I = \frac{B_O - B_I}{A_I - A_O}$$

$$Y_I = A_O X_I + B_O.$$

Count the number of intersections between the specified point and the center of the circle, and between the two points that define a line. If the sum of intersections is odd, the center of the circle is outside the object; however, if the sum is not odd, the center of the circle is inside the object. This procedure also determines if a circle is completely contained inside an object.

For the case where the circle overlaps the object, but there is no valid shortest perpendicular distance from the center of the circle to a side of the object (Figure 9), compute the distance to the nearest point or vertex of the object:

Figure 9

X_1, Y_1 = one of series of points defining object

X_C, Y_C = center of circle

D = distance

R = radius of circle

$$D = \left[(X_1 - X_C)^2 + (Y_1 - Y_C)^2 \right]^{\frac{1}{2}}$$

If D is less than R , the circle overlaps the object.

Figure 10 shows the method of computing the torque for rotating the object as in previous examples. Although this method has not been tested, it is reasonable to assume that it or some variation could be used, not only for packaging and placement, but for hidden line removal or possibly pattern recognition of some sort.

Figure 10

ACKNOWLEDGMENTS

Several people have been helpful in the project, and their efforts and co-operation are appreciated. The author extends thanks in particular to Dr. I. Browning, C. L. Bisson, G. B. Drummond, Jr. and the personnel associated with the computing facilities of Sandia Laboratories, Livermore. N. B. Dinkins drew the diagrams.

APPENDIX

```

PROGRAM TUNNEL
DIMENSION IPRI(500),ARE(500),OCX(500),OCY(500),NOC(500),NOAT(500),
1NORP(500),NPAT(500),XC(500,9),YC(500,9),RC(500,9),IOAT(500,1),
2IORP(500,1),XPAT(500,1),YPAT(500,1)
DIMENSION IDATA(40,10)
DIMENSION DRT(500)

```

C READ IN EXPERIMENTAL OBJECT DATA

```

NOOB=ID=I=0
1 K = 3HEND
L = 6HF INISH
25 ID = ID+1
10 READ 11,(IDATA(ID,J),J=1,10)
11 FORMAT(10A8)
IF (K, EQ, IDATA(ID,1)) 30,20
20 IF (L, EQ, IDATA(ID,1)) 150,25
30 CONTINUE
DECODE (8,31,IDATA(ID,6)) NOOB!
31 FORMAT(I8)
DO 149 IA=1,NOOB!
I=NOOB+IA
READ 111,IPRI(I),ARE(I),OCX(I),OCY(I),NOC(I),NOAT(I),NORP(I),NPAT(
1I)
111 FORMAT(I10,3F10,3,4I10)
J = NOC(I)
READ 121,(XC(I,K),YC(I,K),RC(I,K),K=1,J)
121 FORMAT(9F8,3)
IF (NOAT(I)) 126,133
126 J = NOAT(I)
READ 131,(IOAT(I,K),K=1,J)
131 FORMAT(8I10)
133 IF (NORP(I)) 135,137
135 J = NORP(I)
READ 131,(IORP(I,K),K=1,J)
137 IF (NPAT(I)) 138,149
138 J = NPAT(I)
READ 141,(XPAT(I,K),YPAT(I,K),K=1,J)
141 FORMAT(8F10,3)
149 CONTINUE
NOOB = NOOB + NOOB!
GO TO 1
150 CONTINUE

```

C RANDOM DITHER ON OBJECT X Y COORDINATES

```

DO 809 I=1,NOOB
XM=RANF(-1)*60,-30
YM=RANF(-1)*20,-10
J=NOC(I)
DO 709 K=1,J
XC(I,K)=XC(I,K)+XM
YC(I,K)=YC(I,K)+YM
709 CONTINUE
OCX(I)=OCX(I)+XM
OCY(I)=OCY(I)+YM

```



```

909 CONTINUE
C      INITIALIZE BORDER FORCE
C      INITIALIZE OBJECT OVERLAP FORCE
      FB=10,E10
      FO=10,E4
C      READ IN BOUNDRY DATA
      READ 901, BX0, BY0, BR0, BX1, BY1, BR1
901 FORMAT (6F8,3)
C      INITIALIZE MAXIMUM MOVEMENT STEP SIZE
      SM = 2,
C      INITIALIZE MAXIMUM ROTATION SIZE
      RM = 6,
C      SET NUMBER OF ITERATIONS
      NIT = 200
C      DO LOOP FOR EACH ITERATION
      DO 3999 NI=1,NIT
C      DO LOOP FOR NUMBER OF OBJECTS
      DO 2999 I=1,NOOB
C      SET SUM OF FORCES TO ZERO
      XF = YF = TOR = 0,
C      SET NUMBER OF CIRCLES PER OBJECT
      J = NOC(I)
C      DO LOOP FOR EACH CIRCLE
      DO 1999 K=1,J
C      CALCULATE BOUNDRY FORCE PER CIRCLE PER OBJECT
      XT=BX0-XC(I,K)
      YT=BY0-YC(I,K)
      DTS=XT**2+YT**2
      RSS=(BR0-RC(I,K))**2
      IF(DTS,GT,RSS) 1110,1120
1110 XF=XF+XT*FB
      YF=YF+YT*FB
1120 XT=XC(I,K)-BX1
      YT=YC(I,K)-BY1

```

```

      DTS=XT**2+YT**2
      RSS=(BR)*RC(I,K)**2
      IF(DTS,LT,RSS) 1130,1140
1130  XF=XF+XT*FB
      YF=YF+YT*FB
1140  CONTINUE

C      CHECK FOR NUMBER OF ITERATIONS
      IF (NI ,GT, 100) 1200,1300

C      DO LOOP FOR EACH OBJECT
1200  DO 1229 N=1,N00B
      IF (N ,EQ, 1) 1229,1210
1210  M = N0C(N)

C      DO LOOP FOR EACH CIRCLE
      DO 1219 L=1,M

C      CALCULATE FORCES OF OVERLAP BETWEEN CIRCLES OF DIFFERENT OBJECTS
      XT = -XC(I,K)-XC(N,L)
      YT = YC(I,K)-YC(N,L)
      DSS=XT**2+YT**2
      RSS=(RC(I,K)+RC(N,L)+.01)**2
      IF(DSS,LT,RSS) 1220,1219
1220  XF=XF+XT*FO
      YF=YF+YT*FO
1219  CONTINUE
1229  CONTINUE

C      CHECK FOR NUMBER OF CIRCLES PER OBJECT
1300  IF (J ,EQ, 1) 2020,1310

C      CALCULATE TORQUE PER OBJECT
1310  TOR = TOR+YF*(XC(I,K)-OCX(I))+XF*(YC(I,K)-OCY(I))
1999  CONTINUE

C      CALCULATE AMOUNT OF ROTATION PER OBJECT
      XR = OCX(I)
      YR = OCY(I)
      IF (TOR ,GE, RM) 2100,2110
2100  D = RM
      GO TO 2140
2110  IF (-RM ,GE, TOR) 2120,2130
2120  D = -RM
      GO TO 2140
2130  D = TOR
2140  DO 2149 L=1,J
      XO = XC(I,L)
      YO = YC(I,L)

```

```

      RA0=0,0
      CALL ROTATE (X0,Y0,XN,YN,1,XR,YR,D,RA0)
      XC(I,L) = XN
      YC(I,L) = YN
2149 CONTINUE
      DRT(I)=DRT(I)+D

C      CHECK NUMBER OF ITERATIONS
      2020 IF (NI,GT, 100) 2040,2030

C      SET TILT OR DOWNHILL FORCE
      2030 YF = YF+1,

C      CALCULATE ATTRACTION FORCE OF OBJECTS TO POINTS
      2040 J = NPAT(I)
      DO 1309 L=1,J
      XF = (XPAT(I,L)-OCX(I))/36, + XF
      YF = (YPAT(I,L)-OCY(I))/36, + YF
      1309 CONTINUE

C      CALCULATE ATTRACTION FORCE OF OBJECTS TO OBJECTS
      J = NOAT(I)
      DO 1409 L=1,J
      M = IOAT(I,L)
      XF = (OCX(M)-OCX(I))/36, + XF
      YF = (OCY(M)-OCY(I))/36, + YF
      1409 CONTINUE

C      CALCULATE REPULSION FORCE BETWEEN OBJECTS
      J = NORP(I)
      DO 1509 L=1,J
      M = IORP(I,L)
      XT = OCX(I)-OCX(M)
      YT = OCY(I)-OCY(M)
      DS = (XT*XT)+(YT*YT)
      T = 36./(DS+.001)
      XF = T*XT+XF
      YF = T*YT+YF
      1509 CONTINUE

C      CALCULATE THE MOVEMENT PER OBJECT
      1700 DS = (XF*XF)+(YF*YF)
      IF (DS,GT, (SM*SM)) 1710,1720
      1710 D = SQRT(DS)
      T = SM/D
      XM = T*XF
      YM = T*YF
      GO TO 1730
      1720 XM = XF
      YM = YF

```

```

1730 OCX(I) = OCX(I)+XM
      OCY(I) = OCY(I)+YM
      J = NOC(I)
      DO 1739 L=1,J
        XC(I,L) = XC(I,L)+XM
        YC(I,L) = YC(I,L)+YM
1739 CONTINUE
2999 CONTINUE

C      PRINT NUMBER OF ITERATIONS
      PRINT-2001,NJ
2001 FORMAT(1H,50X,16)

C      CHECK NUMBER OF ITERATIONS
      IF (NJ,GT,180) 2050,2060

C      SET STEP SIZE AND ROTATION SIZE
2050 SM = SM+.1
      RM = RM+.3
2060 CONTINUE

C      PRODUCE BINARY DATA TAPE FOR SC4020 MOVIE PROGRAM
      WRITE(5)(OCX(IH),OCY(IH),DRT(IH),IH=1,5),(OCX(II),OCY(II),RC(II,1)
1,II=6,NOOB)
3999 CONTINUE

C      PRODUCE DATA TAPE FOR CALCOMP PLOTTER FOR CDC C022 PLOTTER ROUTINE
      CALL XYORG(0.0,0.0,120.,120.,10.,10,)
      CALL CIRC(2,,BRO,RX0,BY0)
      CALL CIRC(2,,BRI,RXI,BYI)
      DO 5009 IB=1,NOOB
        KN = NOC(IB)
        DO 5019 KD=1,KN
          CALL CIRC(2,RC(IB,KD),XC(IB,KD),YC(IB,KD))
5019 CONTINUE
5009 CONTINUE
      CALL NXTPLT(15,0,1)

C      PRINT OUT OBJECT PLACEMENT DATA
      NOOB=IB>ID=0
5000 K = 3HEND
      L = 6HFINISH
5005 ID = ID+1
      IF (K,EQ,1)DATA(ID,1) 6030,6010
5010 IF (L,EQ,1)DATA(ID,1) 7000,6020
5020 PRINT 6021, (1DATA(ID,J),J=1,10)
5021 FORMAT(1H,10A8)
      GO TO 6005
5030 DECODE (8,6031,1DATA(ID,6))NOOB
5031 FORMAT(18)

```

```

DO 6059 IA=1,N00B1
  IB=N00B+IA
  PRINT 6041,IB,OCX(IB),OCY(IB),DRT(IB)
5041 FORMAT(1H ,10,/,1H ,5X,OVERALL CENTER*,10X,*ROTATION*,/,1H ,5X,*
1X*,12X,*Y*,/,1H ,3X,3F10,3)
6059 CONTINUE
  N00B=N00B+N00B1
  GO TO 6005
7000 CONTINUE
END

```

```

SUBROUTINE ROTATE (X0,Y0,XN,YN,N,XR,YR,D,RA)
  IF (RA, EQ, 0,0) 20,30
20 RA = D* .017453295
30 XT = X0-XR
  YT = Y0-YR
  R = SQRT(XT**2+YT**2)
  IF (XT, EQ, 0, ,AND, YT, EQ, 0,) 50,40
40 A = ATAN2 (YT,XT),RA
50 XN = COS(A)*R+XR
  YN = SIN(A)*R+YR
  RETURN
END

```

```

SUBROUTINE CIRC(DS,R,XC,YC)
DIMENSION X(900),Y(900)
ORB=0,
JPTS=6,2832/(DS/R)*.5
DT=6,2832/JPTS
ADS=DT*R
JPTS=JPTS+1
DO 109 J=1,JPTS
  X(J)=COS(ORB)*R+XC
  Y(J)=SIN(ORB)*R+YC
  ORB=ORB+DT
109 CONTINUE
  CALL XYPLT(1,1000,0,1,0,X,Y,1,JPTS,1,2,1)
END

```

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