Robots aiding new developments of manipulative machinery

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ROBOTS AIDING NEW DEVELOPMENTS OF MANIPULATIVE MACHINERY

by

NDIANABASI HOGAN JONA UDOAKANG

A Doctoral Thesis submitted in partial fulfilment of the requirements for the award of the degree of Doctor of Philosophy of the Loughborough University of Technology

August 1983

Supervisors: Mr T H Davies, MA, CEng, MIMechE Courtaulds Reader in Mechanisms Dr R Vitols, MTech, PhD, CEng, MIMechE

Department of Mechanical Engineering

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ACKNOWLEDGEMENTS

The author would like to express his sincere gratitude to the following:

The Mechanical Engineering Department for the financial support for the project.

Professors B Downs and G R Wray for guidance as Directors of Research.

Mr T H Davies and Dr R Vitols as supervisors and their guidance and encouragement throughout the period in which this work was undertaken.

Mr T H Davies for his support during the preparation of the thesis.

Mr Alan Slade of the technical staff for the various laboratory preparations.

The Department's machine shop staff for the manufacture of the rig and mechanism.

Mr Ken Topley for the photographs,

and

Mrs Janet Smith for the typing of the work.
ABSTRACT

Application of fixed-arm robots in such manipulative machinery as those used in welding, cutting, packaging etc, has been limited due either to insufficient rigidity in the arm for the transmission of large forces and torques, or to the high cost of improving upon its rigidity.

This work develops a cheap robotic device in the form of a linkage mechanism and tests it on a laboratory rig for positional accuracy. The closed-loop nature of the mechanism ensures sufficient rigidity, and system vibrations are greatly checked. The goal is to use this device for such jobs as the optimization of cam profiles prior to cutting them, guidance of a cutting torch, welding of flat and spherical surfaces, etc. A number of these devices can be arranged around a working space to perform a set of tasks. Put differently, this is an exercise in digital control of machine elements.

The positional accuracy of the device is investigated in the closed-loop control mode. The positions of the DC servo motor shafts are sensed by optical encoders, fed back and compared with the input function which is stored in tables of sequential data in the microprocessor (Rockwell AIM 65, in this case) RAMs. The differences, which are the errors in shaft positions, are fed into digital-to-analogue converters, amplified and used to correct the positions of the motor shafts. The investigation is limited, in this thesis, to a two-axis drive.
Software programmes for both the construction of the data tables, and the motions of the mechanism are developed. Any changes to the path of the motion and speed of the output point of the mechanism can then be made without a re-design of the mechanical components.

Finally, this work is an off-shoot of the automation requirement of the Automatic Rib Transfer Knitting (ART) Mechanism, and reference to this machinery is made frequently in the text.
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CHAPTER 1
INTRODUCTION

This work is the first stage of a research project in the Mechanical Engineering Department of the University of Technology, Loughborough, titled RANDOMM. RANDOMM is the acronym for "Robots Aiding New Developments of Manipulative Machinery". Essentially, this research develops a means of controlling the motions of machine elements automatically using digital control methods. A design tool, RANDOMM is expected to find application in the design of manipulative machinery for use in robot welding, packaging, knitting, cutting etc. It therefore forms, by implication, part of the current world-wide research efforts in the development of industrial robots for increased productivity and quality, or as some literature on similar topics put it, for the eventual freeing of man from arduous, monotonous, dirty and hazardous routine jobs.

1.1 The Objective of the Project

RANDOMM was originally meant to help in the optimization of the design of the Automatic Rib Transfer (ART) machine, which was developed for the textile knitting industry in this Department a few years ago. The ART machine has a set of six machine functions whose respective manipulators are controlled from a single camshaft. The description of its design, functions and its timing diagram
can be found in Woodward\textsuperscript{5}. As in many other applications in which a similar control system is used, the timing and coordination of all the motions of the different manipulators are provided by a set of cam segments mounted on a common camshaft. The camshaft motion is controlled by a hard-wired electrical circuit powered by an electric motor, and the timing of the manipulators by the registration of their input arms on the respective cam surfaces.

It requires good judgement to ascertain before hand that the timing intervals and the displacements will prove satisfactory, and further developments to provide an optimum design are difficult because of the costs and time involved in dismantling and remaking the cam segments. In some cases there could be need to redesign parts of the manipulators as well.

So the purpose of this project is to develop a method for producing and optimizing the cam functions using a microprocessor-controlled device. Once this is done, the cam path can then be cut first time, thus saving the labour involved in a trial-and-error method. By the nature of the task, the manipulator must be made sufficiently rigid to be able to provide sufficient power input into the mechanism it controls and to be able to inscribe the needed path on the material on which the cam path is to be cut.

In the course of the work, a few facts became evident:
1. The strategy was recognised as one that is applicable to the design of any manipulative machinery (hence the research title).
2. A very attractive spin-off became obvious. Our development mechanism can be adapted in its 2-dof form for use in such tasks as the robotic welding of flat plates, and if the device is developed into a 3-dof mechanism for the guidance of a machine element, it can be used for the welding of spherical surfaces. Other direct applications could be made in such other areas as flame or laser cutting, sealing, packaging, etc.

3. A probability exists in which the mechanism can, in certain circumstances, be adapted for incorporation into the machinery itself for dedicated use.

The above requirements therefore call for the development of a 2- and a 3-dof mechanism, or a 2-dof mechanism that can be upgraded into a 3-dof one. Either mechanism should be sufficiently rigid and should have good response to digital control signals.

1.2 Description of the Project

For our 3-dof development mechanism, this work recommends a 10-bar linkage (See Chapter 2) with three input drives. The mechanism can be used in its 2-dof form (which is a 5-bar linkage) with two input drives, or as a geared 5-bar linkage with one input drive, where dedicated use is desired. (Some methods of changing a 5-bar linkage to a geared one for the tracing of certain complex curves, can be found in Tao6).

Partly for reasons of least cost and partly because the first applications of the work are likely to be in plasma or laser cutting and flat welding, a decision was taken to first develop the 5-bar linkage half of the mechanism. The control capability of the entire mechanism is to be undertaken in the next stages of the work.
The 5-bar linkage mechanism, which incidentally simulates a pair of human hands locked together at the wrists, is a very rigid device. This factor alone apparently justifies the difficulty that will be encountered in formulating its software. Apart from its ability to assume very large dimensions, it can be extended into a working space to perform one task or the other and be made to retract to a "park position". Thus a number of these can be mounted around a working area and programmed to carry out a sequence of operations on a workpiece. For example it is possible to have one to do a welding job while the other holds the workpiece and later turns it over for the former to complete the welding of the reverse side.

In its complete 3 dof form, a set of parallelogram linkages provide the wrist configuration to which a grasping mechanism can be attached. The entire mechanism can be mounted on a rack or turret to give it greater versatility.

Two input drives provide control to the motions. They use the latest state-of-the-art servo components, according to 12, for feedback information. Their software control response is excellent. A very compact and portable unit houses the controllers, interface boards and transformers. Power is supplied from an ordinary 230 volts, 13 amps socket.

The rig is meant to probe the accuracy in timing, speed and displacement of the output motion. Both hardware and software methods of controlling this accuracy are considered, though a lot more still has to be done to optimize the sensing of the displacements of the output point.
An AIM 6502 Rockwell Microprocessor (MPU) is used for handling software information. The MPU is available on motherboards for dedicated applications. Command data are stored sequentially in tables in the MPU memories using a high level language, while real time operation of the mechanical load is done in a low level language.

1.3 Merits of the Work

Finally the project satisfies the Science and Engineering Research Council's (SERC) needs in the area of "industrial robots" with "cheaper, lighter linkages", see SRC. We expect the mechanism to have greater rigidity than other manipulators and therefore to operate at higher speeds before encountering vibration levels that would produce unsatisfactory accuracy, and of course there is the training for the author in use and programming of the 6502-based microcomputers.
CHAPTER 2
SURVEY OF KINEMATIC STRUCTURES

In this chapter, an array of kinematic structures from which robotic manipulators can be selected, is compiled. Manipulators already in use are identified. A new one, considered appropriate for the project is selected and further developed. An existing mechanism that can benefit from this work is noted. Finally, the type of actuator for use in providing the input drive is chosen.

Systematics of mechanisms is defined as a basic survey of all possible kinematic structures that can solve a given mechanism-design problem, prior to the working out of such other details as dimensions, etc. By it, an array of structural forms for the envisaged mechanism is displayed for comparison. Such a survey leads not only to ensuring that the set of links and joints worked out can operate as the mechanism, but also to number synthesis (or the knowledge of how many of these links and joints are required) and type synthesis (or the eventual choice of a system such as linkage, cam, hydraulic etc mechanism).

Davies\(^1\) explains the process of number synthesis in relation to planar one-degree-of-freedom linkages. He shows the method of taking a census of all the different families of the envisaged mechanism, demonstrating it with a 10-bar linkage mechanism having 1 dof. Hain\(^3\) gives an example of the application of systematics
to the design of a plough. Before applying systematics to this work, it is first necessary to examine the motions that are commonly found in manipulative machinery.

2.1 Description of Planar Motion

Most of the functions needed in manipulative machinery, e.g. the ART machine, are planar functions. Figure 2.1 shows a body moving in an X-Y plane. Three parameters are needed to describe the position of this body at any instant. P is any reference point on the body, and MN is any axis drawn through P. \( \theta \) measures the attitude of this axis with respect to the x-axis while the x- and y-values locate P. If all three variables (X, Y, \( \theta \)) can be altered independently, or if any pair can be altered independently of the third variable, then the body is said to have 3 degrees of freedom. If \( \theta \) is fixed while the other two vary, the dof of the body reduces to two. Fixing P, but allowing the attitude to change reduces the dof to one, and of course we will have a zero dof if neither the attitude nor the x- and y-values change.

We will imagine this body to be the output member of a mechanism, and will then compile a catalogue of kinematic structures whose output members are capable of producing the 3 dof motion described above.

2.2 Deriving the Kinematic Structures

The reader is referred to 1, 3 and Paul for the definitions of any technical terms used here. Some are, however, reproduced below for convenience.
2.2.1 Related Definitions

1. A planar mechanism is one in which all links undergo planar motions (which, in turn, are defined as motions in which all particles of a given body move in parallel planes).

2. A mechanism is a kinematic chain with one link fixed. This definition is applicable to closed as well as open mechanisms.

3. The Gruebler-Chebyshev criterion states that

\[ F = 3(n-1) - 2g - h \]  

(1)
4. Davies\textsuperscript{1} states that it is the practice in the USA to equate the number of degrees of freedom of a kinematic chain with the number of degrees of mobility of the derived mechanism. Using this concept,

\[ M = F \]  \hspace{1cm} (\text{ii})

5. The loop equation (1), is given for a chain with only lower pairs, by the equation

\[ g = M + 3L \]  \hspace{1cm} (\text{iii})

For all three equations above, \( F \) is the number of degrees of freedom as applied to a chain; \( M \) is the degrees of mobility of the derived mechanism; \( M \) is also the number of actuators needed to control the output link; \( n \) is the number of links in the chain; \( h \) is the number of higher pairs of the chain (it is assumed to be zero in the above analysis); \( g \) is the number of lower pairs, and \( L \) the number of independent loops in the chain.

2.2.2 Compiling the Chains

It is the usual practice, when compiling the kinematic chains to assume as above that all joints are lower pairs. Once the topology of the chain has been established by this assumption, changes in joint formations can then be made. Thus, with the value of \( h \) equal to zero, and \( M = 3 \), Table 2.1 was drawn as follows:
TABLE 2.1: Census of Kinematic Chains with 3-dof

<table>
<thead>
<tr>
<th>L</th>
<th>n</th>
<th>g</th>
<th>No of chains compiled</th>
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<tr>
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<td>3</td>
<td>2</td>
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</tr>
<tr>
<td>5</td>
<td>14</td>
<td>18</td>
<td>-</td>
</tr>
</tbody>
</table>

etc

N.B. The compilation does not have to be exhaustive. In the case above, a satisfactory solution was found without further search.

As can be seen from the table, there is an infinite number of chains that are capable of producing mechanisms whose output links possess 3 dof. It is therefore advisable, for tactical reasons, to examine each set of chains for solutions before going ahead with further compilation. Besides, the positioning accuracy of the output link will decrease with increase in the number of links and joints. Figure 2.2. shows some of the possible chains.

2.3 Selection of the Optimum Mechanism

The next step involves the examination of the different chains for the selection of what may be regarded as the optimum mechanism. Sometimes it may be necessary to modify some links by the creation of double joints in order to enhance perception. For the requirements
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<td><img src="image17.png" alt="Diagram" /></td>
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</table>
FIGURE 2.2
of this work, a set of criteria is applied to facilitate the search.

2.3.1 Criteria for Selection of the Optimum Mechanism

1. The attitude of the output link should be such that it can be altered independently of the X-Y positioning of its reference point. It is necessary also to be able to have the output link maintain a constant attitude when the actuator controlling it is immobilised.

2. The reference point should be able to move along any X-Y path. This includes paths in the X- or Y-directions only.

3. The output link must have a 3 dof motion.

4. The mechanism should have the capability of projecting the output link into and retracting it from a chosen space - possibly to give way to some other operations, within the space, by another device.

5. Preferably, all three actuators should be mountable on the frame member, away from the manipulated or output link. This requirement is necessary for the following reasons:
   i) It eliminates the presence of a "flying" actuator, which would induce an extra mass and inertia requiring additional structural stiffness so as to avoid lower natural frequencies.
   ii) It enhances criterion 4, especially where the space is narrow.
It follows therefore, that the frame member must be a ternary link and not a binary link.

6. The chain with the least number of pairs and links is to be preferred. This condition is derived from the assumption that the positional accuracy of the output link is greatest in a chain with the least number of joints and links.

2.3.2 The Optimum Mechanism

By criteria 3, 4 and 5 chains with zero or one loop are eliminated. By criterion 1, chains with two loops are also eliminated.

Chains in the 3-loop category, however, show, from visual inspection, many possibilities. They are therefore examined in greater detail below. From inspection, the following conclusions were made:

1. Chains (13) and (14) do not satisfy criterion 1.
2. Chain (15) satisfies criterion 2 but not criterion 1.
3. Chain (16) appears to satisfy all the criteria after the modification shown in Figure 2.3(a) and is therefore shortlisted.
4. Also shortlisted are chains having one quarternary link and two ternary links.
5. Chains with two quarternary links do not satisfy criterion 5. These are chains (26), (30), (31) and (32).
6. Chains with one 5-sided links do not also satisfy criterion 4. They are (27), (28) and (29).

Chains (16), (17), (18), (19), (20), (21), (23), (24) and (25) are re-drawn in modified forms (Figure 2.3(a), (b), (c), (d), (e), (f), (g), (h) and (i), respectively) for further examination. The arrowed links are the output links, and joints marked "+" are their reference points.

At this stage a pattern begins to emerge. There is the single 5- or 6-link loop for the production of x-y motions and two-loop combination for rotating the output member. Three of the chains have a faulty mechanism for producing rotations. These are chains (c), (d) and (h). They cannot therefore satisfy criterion 1. Another three (e), (f) and (g), each have to locate the reference point with three parameters. This means that they cannot satisfy criterion 5. So chains (a), (b) and (i) become possible solutions.

In order to control the rotations of the output link from the frame it is desirable to have its angular motions equal to those of the crank that operates it. This situation can be brought about by the use of parallelogram linkages. The mechanism of Figure 2.3(a) does not satisfy this additional requirement, but those of Figures 2.3(b) and (i) do, and the final configuration is given in Figure 2.4. It consists of a 5-bar loop ABCDE used in locating the X-Y point, and two sets of parallelogram linkages DEFG and CDHI for controlling the output bar CI. HDG is a bell crank and AE is the frame member. The three actuating cranks are AB, ED, and EF, with the last two cranks having coincident frame pivot axes.
FIGURE 2.4
At this point, further examination of chains with 4 loops for solution becomes unnecessary except if the above solution later proves inadequate for our purposes. The next stage consists of choosing the mechanism type.

2.3.3 **Type Synthesis**

Altering the formation of the various joints in the chosen mechanism results in different types of mechanisms. The best type is not always an all-lower-pair (or linkage) mechanism, but the writer was not able to find a non-linkage solution that satisfied criterion 4 of Section 2.3.1. So the solution in Figure 2.4 was upheld, and this is the RANDOMM mechanism.

Due to the least cost strategy mentioned in Chapter 1, this mechanism will be tested first for the positioning accuracy of the output point C. That means developing first, the 5-bar linkage half of it.

It is important to note that many functions of manipulative machinery are not of the 3 dof type. For instance, of the six functions of the ART machine only one is of the 3 dof category. The others are of 1 dof. The 3 dof function may be seen in Figure 3.6. It consists of the motion of a bar of knitting needles at constant attitude along the path, ABDC, and back either along the same path or along a new path (e.g. CA). The application of 2 dof motions abound, however, in such processes as cutting and welding. So the development of the 5-bar (or the 2 dof half of the mechanism)
is equally important, and can itself be applied directly in many machines.

It becomes important, therefore, to consider other mechanism types producible from the 5-bar. Figure 2.5 shows six possible means of producing 2-dof motions. By exchanging joints B and D with prismatic or cylindrical pairs the mechanism of Figure 2.5(b) can be derived. Changing only joints A and E from revolute to prismatic or cylindrical pairs results in the mechanism of Figure 2.5(c).

In Figure 2.5(d), joints B and D are exchanged into screw pairs. Links BC and DC are made into blocks and mounted at right angles to each other so that the top block DC carries the output point. While link AB is confined only to rotary motions, link OD is allowed to both rotate and slide along the frame. In a similar formation the mechanism of Figure 2.5(e) is derived by making C a planar pair and joints B and D screw pairs.

The mechanism of Figure 2.5(d) is used extensively as X-Y tables. That of Figure 2.5(e) is derived from Mechanism No 2493 of Artobolevsky's catalogues 4. None of the two satisfies our criterion number 4(b), and are therefore discarded. They are worthy of being mentioned because they are already in use and are comparable with the 5-bar linkage.

The mechanisms of Figure 2.5(b) and (c) will require hydraulic or pneumatic actuators for their motions. A schematic of their type of system is shown, complete with the major control components,
FIGURE 2.5: Two-dof mechanisms
FIGURE 2.6: Schematic of the Hydraulic Control System
in Figure 2.6. The diagram is developed from (25).

It is necessary to note here that mechanism 1 of Figure 2.2 is used commonly in fixed arm robots. Another 2-dof mechanism in use is shown in Figure 2.5(f). It is derived from the equivalent chain shown beside it. It might also be noted that the application of digital control to some existing mechanisms of the 4-loop category can become plausible. In particular, there is the mechanism number 37 of Figure 2.2, which is developed into the forms shown in Figure 2.7. Used extensively in earthmoving machinery, its robotic control could make work in severe weather conditions a pleasure.

So Figure 2.2 may thus act as a mechanism bank from which to obtain guidance on the selection of 2- or 3-dof planar mechanisms. A guide to the selection of 4-bar linkage mechanisms for the tracing of coupler curves is obtainable from the yet unpublished work of Davies and Shang of the Department.
The next stage of the work examines the various available actuators.

2.4 Choice of Actuators

There are various types of programmable actuators. These include:

1. Stepper Motors
2. Electrohydraulic Stepper Motors
3. Hydraulic Motors
4. Servo Motors (including versions of it such as torque motors and gear motors).

Stepper motors are known to have inherent resonance problems at low speeds. The number of steps per revolution is limited to about 2000, in the most recent models. Hydraulic and electrohydraulic stepper motors have low response to input pulses and have become less used in numerical control. The best option therefore (and the latest state-of-the-art) is the AC or DC servo motor. In a typical application, a moving coil servo motor can be accelerated from zero to 2500 rpm and back to zero five hundred times in a second. The moving coil DC servo motor is one of several permanent magnet servo motors commonly used. Others include torque motors, iron core motors, surface wound motors and printed armature servo motors.

Torque motors are direct drive motors having the highest practical torque-to-inertia ratio. They are coupled directly to
the mechanical load. A gear train decreases the torque-to-inertia ratio by a multiple equal to the gear ratio. This results in poorer acceleration capability. Since torque motors have no gearing they produce the highest accuracy in a positioning or speed-control system. Gear motors, on the other hand, are servo motors with integrally mounted gears. All servo components are available for position and speed control. But models available to the writer (from Unimatic Engineers Ltd) had low output torques.

2.5 Advantages of the Linkage Option

As was mentioned earlier on, there is the option, for a 2 dof mechanism, of choosing either the linkage or the hydraulic solutions. A cost evaluation for the latter (Figure 2.6), was put at £6792.00 at the time. That for the former was put at £2500.00. Both costs did not include the microcomputer and the associated peripherals. So quite logically, a decision to discard the hydraulic option, at least for the time being, was taken.

Some of the merits for the linkage option include:

1. A high structural stiffness of the mechanism;
2. The ability of the mechanism to be made easily in large or small dimensions;
3. Low cost;
4. The ability to accept actuators with fast response to input changes - which means high speed operations;
5. The ability, even with the third drive, to project into and retract from a given space;
6. The ability of checking the system from undue vibrations, by the use of counterbalance weights for the links; and
7. The ability to have all its actuators grounded, thus making the links less massive.
CHAPTER 3
KINEMATIC AND DYNAMIC ANALYSES

This chapter establishes the necessary data for the design of the mechanism.

Based on the requirements of the ART and another textile handling machine the following major specifications were made:

1. The maximum stroke or displacement of the reference point C = 250 mm.

2. The maximum speed of C = 1 cycle/sec along a 250 mm diameter circle or 1 cycle in a tenth of a second along a circle of 25 mm diameter, both of which yield a maximum linear speed of 0.79 m/s.

3. The mechanism is to be tested in three loading modes viz - vertically in a vertical mode, vertically in a horizontal mode and horizontally in a horizontal mode (see Section 4.1).

4. Any path to be traced by point C must be located within the 250 mm diameter circle, hereinafter referred to as the "Specified area" (of operation of the mechanism), but because the analysis will be carried out for the motion of point C at a constant maximum speed of 1 cycle/sec, it is assumed that the speed requirements for other paths will not give rise to torque requirements that are more demanding than they are when point C is traversing the periphery of the specified area.
The remaining data were derived from the relative position
and dynamic analyses of the mechanism.

3.1 Relative Position Analysis (RPA)

Relative Position Analysis is a mathematical determination
of the Cartesian coordinates of the principal points on the mechanism
at any instant of time, as its output point traces a given path.
It is used here to relate the positions of C to the crank angles,
and to confirm the ability of the mechanism to produce desired
motions for a given set of link lengths.

3.1.1 General Layout of the Mechanism

Figure 3.1 shows this layout.

Referring to the figure:

A(O, 0) is a frame pivot and is placed at the origin of the X-Y
plane.
E(X5,Y5) is the second frame pivot.
F(X6,Y6) is the fixed point designating the centres of the two
circles referred to in the specification.
B(X2,Y2), C(X,Y) and D(X4,Y4) are the respective locations for joints
B, C and D.
AE, AB, BC, CD and DE represent the centre lines of the five links.
AE is the frame link. All five are designated in magnitudes by
L1, L2, L3, L4 and L5 and in directions, with respect to the x-axis,
by zero, A2, A3, A4 and A5 respectively.
FIGURE 3.1: The 5-bar Linkage Mechanism
Lines FC, AC and CE (with magnitudes L6, L7 and L8, and directions A6, A7 and A8 respectively) are also given.

For each position of C, the directions of lines AB, AC, CD and DE have alternative positions which are indicated by the dashed lines AB', B'C, CD' and D'E, with directions A2', A3', A4' and A5' respectively.

3.1.2 Mathematical Relationships

Using the specified parameters above:

\[ L_7 = \sqrt{x^2 + y^2} \]  

(i)

\[ \tan(A_7) = \frac{y}{x} \]

(ii)

Considering triangle ABC

\[ \cos(A_2-A_7) = \frac{L_2^2 + L_7^2 - L_3^2}{2L_2L_7} \]

(iii)

\[ \text{giving } A_2 = \tan^{-1}\left[\frac{y}{x}\right] + \cos^{-1}\left[\frac{(L_2^2+x^2+y^2-L_3^2)}{2L_2\sqrt{x^2+y^2}}\right] \]

(iii)(a)

The alternative value for this angle is

\[ A_2' = \tan^{-1}\left[\frac{y}{x}\right] - \cos^{-1}\left[\frac{(L_2^2+x^2+y^2-L_3^2)}{2L_2\sqrt{x^2+y^2}}\right] \]

(iii)(b)

if vectors AB' and B'C are considered.
\[
\tan (180 - A8) = Y / (L1 - X),
\]

\[.
A8 = 180 - \tan^{-1} \left[ Y / (L1 - X) \right] \tag{iv}
\]

\[
(A8 - A5) = \cos^{-1} \left[ \left( L8^2 + L5^2 - L4^2 \right) / (2 \cdot L5 \cdot L8) \right] \tag{v}
\]

\[
L8 = \sqrt{(L1 - X)^2 + Y^2} \tag{vi}
\]

whence

\[
A5 = 180 - \tan^{-1} \left[ Y / (L1 - X) \right] - \cos^{-1} \left[ \frac{((L1-X)^2 + Y^2 + L5^2 - L4^2)}{2 \cdot L5 \cdot \sqrt{(L1-X)^2 + Y^2}} \right] \tag{vii}(a)
\]

and

\[
A5' = 180 - \tan^{-1} \left[ Y / (L1 - X) \right] + \cos^{-1} \left[ \frac{((L1-X)^2 + Y^2 + L5^2 - L4^2)}{2 \cdot L5 \cdot \sqrt{(L1-X)^2 + Y^2}} \right] \tag{vii}(b)
\]

for the alternative position.

\[
XB = L2 \cos A2 \tag{viii}
\]

\[
YB = L2 \sin A2 \tag{ix}
\]

\[
A3 = \cos^{-1} \left[ (X - XB) / L3 \right] \tag{x}
\]

\[
XD = L1 + L5 \cos A5 \tag{xi}
\]

\[
YD = L5 \sin A5 \tag{xii}
\]

\[
A4 = 180 - \cos^{-1} \left[ (XD - X) / L4 \right] \tag{xiii}
\]
3.1.3 Modes of Operation

As can be seen from the geometry of Figure 3.1 and from the mathematical relationships in sub-section 3.1.2, the positions of joints B and D are not unique for each position of C. As a result the mechanism can assume any of the four configurations given in Figure 3.2. This yields four modes of operation for the linkage. The alternative positions of the links are indicated in Figure 3.1 as AB'CD'E and defined by equations (iii)(b) and (vii)(b) above.

A decision was taken to have the mechanism operate in the Mode 1 configuration. In this mode it has symmetry and good transmission angles (given by the value A4-A3).

3.1.4 Determination of Link Lengths

A graphic layout was made. In it, the lengths of the cranks were assumed as 21.52 cm, and the distance between the two frame pivots as 45.1 cm. The specified working area, a circle of diameter 25 cm, was placed with its centre on the axis of symmetry of the mechanism and at distance 44 cm above the frame pivots. At that location the mechanism would operate with its transmission angle as close as possible to 90°. It was also ensured that the locus of point C for which the transmission angle is 90° passes through the centre of this working area. Thus a high quality of motion transmission was assured. This method yielded the value of 44 cm for each coupler length. Again equal lengths were assumed to ensure symmetry.
FIGURE 3.2

- Mode 1 (a)
- Mode 2 (b)
- Mode 3 (c)
- Mode 4 (d)

Specified area working envelope of Point C
The size of the working envelope for point C, based on a transmission angle range of 40° to 150°, is indicated in the figure. Line C'CC" is the complete locus of point C within the envelope when the mechanism is operated with the maximum transmission angle of 90°.

3.2 Programmes for Relative Position Analysis (RPA)

This analysis uses the various mathematical relationships and the graphically derived lengths to give a visual perception of the capability of the mechanism to trace certain specified paths, tests the graphically derived lengths for correctness, and lists the various angular data for the links. The paths are:

1. a 250 mm diameter circle,
2. a 25 mm diameter circle, and
3. a park-start position straight line

The first follows directly from our specification of this circle as the limit of our working area for the mechanism. The second was an after thought suggested as a result of a requirement in knitting operations, and the third follows from our desire to make the mechanism able to project its output point into a given area and retract to a rest position. This means that for every path to be traced, there must be this initial routine to move point C from a rest or park position to the starting point of the path.

The programme for the three paths is written in Basic (and labelled "PARM 15") for the Tektronix 4051 minicomputer in the
Department. It is located in Appendix A. The plots are shown in Figures 3.3, 3.4 and 3.5. As indicated in the figures both circles were located with their centres at F(22.55, 44), for symmetry.

The plot was additionally made for one of the functions of the ART machine, Figure 3.6, which is shown as ABCDA in the diagram.

All plots are made to a scale of 1:6.4 approximately.

3.2.1 Optimizing the Lengths

The plots show that the graphically derived lengths are correct. They are re-specified as follows:

- \( L_1 = 45.1 \text{ cm} \)
- \( L_2 = L_5 = 21.52 \text{ cm} \)
- \( L_3 = L_4 = 44 \text{ cm} \)
- F is the point F(22.55, 44).

3.2.2 Programmes and Results (Circular Paths)

It was necessary to make a quick check from calculator - and graphically derived values to ascertain the authenticity of these data, and hence the equations. Data for five of the positions of Point C, are given in Table 3.1 as derived by all three methods. They compare favourably, within the limits of measuring errors.
FIGURE 3.4: POSITION PLOT FOR RANDOM MECHANISM
FIGURE 3.5: POSITION PLOT FOR RANDOMM MECHANISM: PARK-START MOTION
FIGURE 3.6: POSITION PLOT FOR RANDOM MECHANISM
TABLE 3.1:

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<th>Calculator Values (degrees)</th>
<th>Computer Values (degrees)</th>
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A second table, Table 3.2, carries sections of the computer printouts. It indicates the maximum and minimum values of the two crank angles and the positions of C, with respect to the x-axis, when these occur. For the circle of 250 mm diameter, the largest variation in each set of crank angles is 71.85°.

Similar values may be derived for the 25 mm diameter circle, but are unnecessary here. If derived, the largest and smallest values of each set of crank angles would lie within the limits of the range of values for the 250 mm diameter circle (Refer to Figure 3.5).

3.2.3 Results for Straight Line Path

The "park-position" of the mechanism was arbitrarily, though conveniently, fixed at the position in which point C assumes the position P(22.55,20). The "start position", S, is that in which C is at the start of any given path. The programme for the Park-to-Start (P-S) motion is written generally for any P-S straight line motion. By specifying S, it can be adapted for any given straight line path. For the 250 mm diameter circle, S is defined as point S(35.05, 44).

The position plot for this path is given in Figure 3.4. The maximum and minimum crank angle values are as follows:

\[ A_2 \text{ max } = 157.4^\circ \]
\[ A_2 \text{ min } = 97.14^\circ \]
A5 max = 30.98°
A5 min = 15.29°

3.3 Dynamic Analysis

This analysis establishes the remaining design data such as, the maximum bearing forces, the maximum applied torques at the frame pivots and the maximum speed of the cranks.

In the analysis, use was made of a method developed by Mr T H Davies of the Department. The method was meant for one-degree-of-freedom linkage mechanisms, but by modifying the 5-bar linkage it was possible to apply the method for its analysis.

3.3.1 The Modified 5-bar Linkage Mechanism

By converting the length CF (Figure 3.1) into a fictitious link and making point F a frame pivot, along with A and E, the mechanism changes into a Watt's or Stephenson's 6-bar linkage, with one of the ternary links as the frame member and the other as the driving member (i.e. with 1 dof for the output link).

The explanation for this change and the validity for it is illustrated in Figure 3.7. In it, the double joint is expanded to make link CF a ternary link, thereby producing the Watt's 6-bar linkage mechanism, Figure 3.7(b). If on the other hand, link GD (or CB) is changed into a ternary link, a Stephenson's mechanism is formed (Figure 3.7(c)).
FIGURE 3.7a: The Modified 5-bar Linkage

Figure 3.7a is re-drawn in Figure 3.8 and given additional nomenclature for use in the development of a computer programme for the analysis. The programme is written in Fortran for the main frame computer of the University. It incorporates an RPA programme.

In the figure:
F is the origin
V is the angle link FC makes with the x-axis
R1, R2 etc are the angular positions of links 1, 2 etc w.r.t. the x-axis.
G1, G2 etc are the centres of gravity of links 1, 2, etc.
Link 1 is the driving member.
A, E and F are frame pivots.
Angles XAC and XEC are angles made respectively by lines AC and EC with the x-axis.
L(1) = AF
L(2) = EF
L(3) = FG1
L(4) = FC
L(5) = BC
L(6) = CG3
L(7) = AB3
L(8) = BG
L(9) = CD2
L(10) = CG
L(11) = ED
L(12) = DG5

A(1) = Angle xFA
A(2) = " xFE
A(3) = " CFG1
A(4) = " BCG3
A(5) = " ABG2
A(6) = " DCG4
A(7) = " EDG5

N.B. The slight inconsistencies in nomenclature is due to the fact that Figures 3.1 and 3.8 refer to two different programmes.

FIGURE 3.8
3.3.2 Bearings Analysis

As mentioned earlier on, the RPA programmes were used to optimize the lengths of the links. Up to this point, these links have been assumed massless.

A Bearings Analysis puts the system in a dynamic state, and calculates relevant data for use in designing the bearings and in determining link sizes (and hence, their respective masses and moments of inertia). It also produces values for the determination of the maximum torques at the frame pivots for use in the selection of actuators.

In the analysis, each link of the mechanism is considered in both its static and its dynamic loading states. Corresponding forces are then equated and this results in a set of simultaneous equations for use in solving for the values of applied torques and bearing forces.

Figure 3.9 shows link 2 in the two loadings. Two figures (a) and (b) are drawn for each link in order not to congest one figure.

T2 is the applied torque on member 2
M2 is the mass of member 2 and
I2 its mass moment of inertia
Ax is the x-component of the bearing load at A
Ay, the y-component of the bearing load at A
Bx is the x-component of the bearing load at B.
By is the y-component of the bearing load at B
X(2) is the x-coordinate of the centroid G2
Y(2) is the y-coordinate of the centroid G2
XA, YA and XB, YB are the X, Y coordinates of points A and B respectively.
R(2) is the angle of rotation of link 2
R1(i) is the 1st derivative of R(i) w.r.t. V
R2(i) is the 2nd derivative of R(i) w.r.t. V
X1(i), Y1(i) is the 1st derivative of X(i), Y(i) w.r.t. V.
X2(i), Y2(i) is the 2nd derivative of X(i), Y(i) w.r.t. V.

An explanation of the various relationships using link 2 as a representative member follows.

From Newton's second law of motion,

\[ \frac{dY(2)}{dt} = \frac{dY(2)}{dv} \cdot \frac{dv}{dt} \]

\[ \frac{d}{dt} \left( \frac{dY(2)}{dt} \right) = \frac{dY(2)}{dv} \cdot \frac{d^2v}{dt^2} + \frac{d^2Y(2)}{dv \; dt} \cdot \frac{dv}{dt} \]

\[ = \frac{d^2Y(2)}{dv^2} \cdot \frac{dv}{dt} \cdot \frac{dv}{dt} \cdot \left( \frac{d^2v}{dt^2} = 0 \right) \]

\[ \therefore \frac{d^2Y(2)}{dt^2} = \frac{d^2Y(2)}{dv^2} \left( \frac{dv}{dt} \right)^2 \]

\[ = \omega^2 \left( \frac{d^2Y(2)}{dv^2} \right), \left( \frac{dv}{dt} = \omega = \text{const} \right) \]

Designating \( \frac{d^2Y(2)}{dv^2} \) as \( Y2(2) \)

\[ \frac{d^2Y(2)}{dt^2} = Y2(2) \times \omega^2. \]
This value is the linear acceleration of link 2 in the y-direction. Similarly,

\[ \frac{d^2 R(2)}{dt^2} = R2(2) \times \omega^2 \]

and represents the angular acceleration of link 2.

For a system in dynamic balance the sum of applied forces in the x-direction must equal the sum of the inertia forces in the x-direction. The same goes also for forces in the y-direction. As a result,

\[
\begin{align*}
A_x - B_x &= m_2 X2(2) \omega^2 \\
A_y - B_y &= m_2 Y2(2) \omega^2 \\
A_x (Y2 - YA) - A_y (X2 -XA) + B_y (XB - X2) \\
+ B_x (YB - Y2) + T2 &= I_2 R2(2) \omega^2
\end{align*}
\]

(iii)

Considering the forces in link 3 (Figure 3.10)

\[
\begin{align*}
B_y - C_y &= m_3 Y2(3) \omega^2 \\
B_x - C_x &= m_3 X2(3) \omega^2 \\
B_x (Y3 - YB) + B_y (XB - X3) + C_x (YC - Y3) + C_y (X3 - XC) \\
&= I_3 R2(3) \omega^2
\end{align*}
\]

(iv) (v) (vi)
From Figure 3.11

\[ C_x - D_x = m_4 \times 2(4) \omega^2 \]  
\[ C_y - D_y = m_4 \times 2(4) \omega^2 \]  
\[ C_x (Y4 - YC) + C_y (XC - X4) + D_x (YD - Y4) + D_y (X4 - XD) = I_4 \times R2(4) \omega^2 \]
In Figure 3.12

\[ D_x - E_x = m_5 X2(5) \omega^2 \]  \hspace{1cm} (x)

\[ D_y - E_y = m_5 Y2(5) \omega^2 \]  \hspace{1cm} (xi)
\[ D_y (X_D - X_5) + D_x (Y_5 - Y_D) + E_y (X_5 - X_E) + \]

\[ E_x (Y_E - Y_5) + T_5 = I_5 R_2(5) \omega^2 \]
Analysis for link 1 is left out since we are only interested in the links of the 5-bar mechanism.

The twelve simultaneous equations are re-arranged and represented in the matrix form shown in Figure 3.13. The re-arrangement is necessary in order to satisfy the NAG routine requirement for solving simultaneous equations. The routine requires that there be no zeroes in the leading diagonal of the left hand matrix. The solution was provided by Mr T H Davies of the Department using two Fortran subroutines in the main frame computer of the Loughborough University of Technology. One of the subroutines is the Relative Position Analysis (RPA) subroutine and the other is the Bearings (BRGWRITE) subroutine. The former is the Fortran equivalent of the programme mentioned in Section 3.2.
| 1 0 -1 0 0 0 0 0 0 0 0 0 0 0 0 0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 1 0 -1 0 0 0 0 0 0 0 0 0 0 0 0 |
| 0 0 1 0 -1 0 0 0 0 0 0 0 0 0 0 0 |
| 0 0 0 1 0 -1 0 0 0 0 0 0 0 0 0 0 |
| 0 0 0 0 1 0 -1 0 0 0 0 0 0 0 0 0 |
| 0 0 Y3- YB 0 0 0 0 0 0 0 0 0 0 0 0 0 |
| 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 |
| 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 |
| 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 |
| 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 |
| 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 |
| 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 |
| 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 |
| 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 |
| Y2- YA X2 Y2- XB X2 | 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 |
| 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 |
| 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 |
| 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 |
| 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 |
| 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 |
| 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 |
| 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 |

**FIGURE 3.13**
CHAPTER 4

DESIGN OF THE RANDOM MECHANISM

In this chapter, values of the masses and mass moments of inertia of the various links are determined. They are used in the Bearings Analysis Programme of Chapter 3 to determine the values of the various design parameters. Production drawings for both the mechanism and its rig are also given.

4.1 Loading of the Mechanism

As was mentioned in Chapter 3, the mechanism will be considered throughout this work in its Mode 1 configuration. But there is also the loading mode to be considered. In a practical application, a load will be attached to the output point C. Depending on the orientation of the mechanism, the force at C will act in any of three different directions. Figure 4.1 gives these directions as the x-, y- or z- directions in an xyz coordinate system.
In the mode 1 loading, the force is applied in the z-direction. In the loading modes 2 and 3 it is applied in the y- and x-directions respectively. So the rigidity of the mechanism must be ascertained for all three loading modes.

Any mass attached to the output point C, will exert not only its own weight on the mechanism but also a centripetal force, if, for instance, it is made to move along a circular path. Thus for a load of mass \( m = 45.4 \text{ kg or } 100 \text{ lb} \), moving at an angular velocity \( \omega = 2\pi \text{ rad/sec} \) along the perimeter of our specified area (radius = \( r \)), a constant centripetal force \( = mr\omega^2 \) of 223N is induced. This force may have a component in the direction of the gravitational force depending on the loading mode adopted.

In the loading mode 1, the gravitational force is perpendicular to the centripetal force and the latter has no effect on the former, but in the modes 2 and 3 loading, its full value acts in the same direction as the gravitational force once per cycle, as point C traces the circle. For example, in the mode 2 loading this situation occurs when C is at the bottom most point of the 250 mm diameter circle. The total force acting at C at that instant becomes 668N.

To have the system balanced, counter-balance weights are introduced on each crank and coupler. Details of the balancing method are given later in Section 4.3.
4.2 Rigidity Considerations

In determining the structural rigidity of the mechanism the following assumptions were made:

1. That during operations the mechanism reaches a position in which the full load applied at C is borne entirely by one of its two arms.

2. That the length of the arm in that position equals the total length of the crank and the coupler when in a stretched-out, or colinear formation.

3. That the cross-sections of the cranks and the couplers are identical.

Rigidity considerations are based on the ability of the mechanism to resist deflections due to the various forces acting on it.

4.2.1 Deflection in Loading Mode 1

In the Mode 1 loading, joint B (see Figure 4.2) is regarded as rigid and the maximum deflection will occur at point C - the arm, acting as a cantilever of length \((l_2 + l_3)\). The worst deflection will occur in the counterbalanced mechanism. Referring to the nomenclature given for Figure 4.2

\[
\theta_B = (M_{BC} - M_{BB}) \frac{l_2}{EI_2} + \frac{m g A_2 l_2^3}{6 EI_2} + \frac{(F_B + F_C)}{2 EI_2} l_2^2
\]  

(1)
\[ \delta_B = (M_{BC} - M_{BB}) \frac{z_2^2}{2EI_2} + \frac{mg A_2 z_2^4}{8EI_2} + \frac{(F_B + F_C)}{3EI_2} z_2^3 \] (2)

\[ \delta_C = \delta_B + \theta_B \xi_3 \] (3)

After several trials the sections shown in Figure 4.2(c) were chosen for the coupler and the crank. The choice of a rectangular, tubular section for the crank was based principally on the ease of making a rigid weld onto the drive shaft. The two pipes were placed 9 cm apart. Those of the coupler were placed 4.5 cm apart. Both tubes are hot finished seamless steel tubes.

From equation (1):

\[ \theta_B = (445 \times 44-77) \frac{21.52}{EI_2} + 3.42 \times 0.077 \times 21.52^3 + \frac{(445 + 11)(21.52^2)}{2EI_2} \]

\[ = 3.53 \times 10^{-4} \text{ rads} \]

From equation (2):

\[ \delta_B = (445 \times 44-77) \frac{21.52^2}{2EI_2} + \frac{0.077 \times 3.42 \times 21.52^4}{8EI_2} + \frac{(445 + 11) 21.52^3}{3EI_2} \]

\[ = 4.02 \times 10^{-3} \text{ cm} \]
FIGURE 4.2

Cross-section of crank

Cross-section of coupler
Referring to Figure 4.2:

\( \ell_2 = \text{length of crank} = 21.52 \text{ cm} \)
\( \ell_3 = \text{length of coupler} = 44 \text{ cm} \)
\( I_2 = \text{area moment of inertia of crank} = 71.559 \text{ cm}^4 \)
\( I_3 = \text{area moment of inertia of coupler} = 7.452 \text{ cm}^4 \)
\( A_2 = \text{area of cross-section of crank} = 3.42 \text{ cm}^2 \)
\( A_3 = \text{area of cross-section of coupler} = 1.472 \text{ cm}^2 \)
\( mg/\ell \) is the weight per unit length of crank = 0.077 \( A_2 \) N
\( F_B \) is the weight of the counterbalance = 11N and acting 7 cm from B
\( F_C \) is the applied load at C
\( R_A \) is the frame reaction at fixed end A
\( M_{BB} \) is the bending moment of the counterbalance at point B
\( = 7 \text{ cm away from the centre of mass of the C' balance} = 77 \text{ N-cm} \)
\( M_{BC} \) is the bending moment of \( F_C \) at point B = 445 \times 44 \text{ N-cm}
\( \delta_B \) is the deflection at B
\( \theta_B \) is the slope of the elastic line at B
\( \delta_C \) is the deflection of the entire arm at C
\( E \) is Youngs Modulus for steel = 210 \times 10^5 \text{ N/cm}^2

In Figure 4.2(b) BC represents a massless coupler with no force at C.
From equation (3):

\[ \delta_c = \delta_{\text{max}} = 0.0196 \text{ cm} \]

This deflection value is tolerable.

4.2.2 Shearing at the Pivots

The shear forces at the frame pivots depend on the applied load at point C of the mechanism and on the mass of the arm itself. Thus with F equal to 668N, and force induced by the masses of the arm equal to 197N, the shear stress,

\[ F_s = \frac{(861/3.42) \text{N}}{\text{cm}^2} \text{ or } 252 \text{ N/cm}^2. \]

For steel, the allowable shear stress is given as 2100 N/cm². Therefore the above value is safe.

4.2.3 Deflection in Loading Mode 2

In this mode each arm of the mechanism takes on its maximum loading when it is in a stretched out formation. The arm would therefore be considered as being made up of two pin-ended columns joined end to end, and the theory of columns applies.

The critical load, \( P_{\text{cr}} \), for a steel column of length \( \ell \), area moment of inertia \( I \), and Youngs Modulus of Elasticity \( E \), is given by the Euler equation:

\[ P_{\text{cr}} = \frac{\pi^2 EI}{\ell^2} \]
which equals \( \frac{\pi^2 \times 210 \times 10^5 \times 9.6}{44^2} \) N

\[ = 1.03 \times 10^6 \text{ N for the couplers} \]

and, approximately, \( \frac{\pi^2 \times 210 \times 10^5 \times 71.56}{21.52^2} \) N

\[ = 3.2 \times 10^7 \text{ N, for the cranks.} \]

These values are much higher than the maximum resultant force of 669N, acting at C in the mode 2 or 3 loading.

4.3 Balancing Considerations

Provisions are made for the use of counterbalance weights that will eliminate shaking forces, in case the shaking of the framework is detrimental. This is one means of optimizing the positional accuracy of the mechanism. Unchecked shaking forces can lead to an inaccurate tracing of the path of point C.

The method adopted is quite simple. It brings the centre of gravity of the entire mechanism to the mid-point of the centre line joining the two frame pivots (Figure 4.4). Extension arms on which to attach counterbalance weights are provided for each coupler and crank. So irrespective of the value of the applied force at C, counterbalance can still be provided. The effect of the method makes the couplers, BC and CD "massless" but places their full weights at their centroids B and D.
With regards to the cranks, A and E are the two centroids. Their counterbalance weights counterbalance both the weights of AB, or ED, and the entire weight of the attached coupler. The system's symmetry therefore places the centre of mass at J midway between A and E.

Determination of the weights to be used in the counterbalance is done by use of the simple lever principle. Moments of the forces are taken about B for couplers BC and A for crank AB.

But there is a price to be paid. The introduction of counterbalance raises the value of the maximum torques that act at the frame pivots, and hence the sizes of the servomotors, and the
shaking moment about the system's centre of gravity will therefore be higher.

4.4 Masses and Inertia of the Links

Figure 4.5 shows sketches of the coupler and the crank. Reference should be made to the actual drawings in Plates 2 and 3 where the relevant data are obtained for the calculations.

Table 4.1 shows values of the masses and mass moments of inertia of the different elements (shown in Figure 4.5) and of the couplers and the cranks. Minor structural differences in the two couplers are discarded in the computation. In the table:

- \( d \) is the distance between the centre of mass of the element from the centroid of the coupler, \( X-X \), or of the crank, \( Y-Y \).
- \( M \) is the mass of the element
- \( I_G \) is the mass moment of inertia of the element about its centre of mass
- \( I_{XX}, I_{YY} \) the moment of inertia of the respective element about \( X-X \) or \( Y-Y \)

Element \( H \) represents the coupler's counterbalance weight derived by use of the lever principle with the centre of gravity of \( H \) at 7 cm from \( X-X \), while \( F \) represents the crank's counterbalance weight with its centre of gravity 10.5 cm from the \( Y-Y \) axis.
FIGURE 4.5
### TABLE 4.1

Mass and Inertia Values for the Couplers

<table>
<thead>
<tr>
<th>Element</th>
<th>Mass, M (kg)</th>
<th>d (m)</th>
<th>( I_G ) (kg·m²)</th>
<th>( Md^2 ) (kg·m²)</th>
<th>( I_{xx} ) (kg·m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.143</td>
<td>0.440</td>
<td>0.49x10⁻³</td>
<td>0.028</td>
<td>0.029</td>
</tr>
<tr>
<td>B</td>
<td>0.375</td>
<td>0.220</td>
<td>5.4x10⁻³</td>
<td>0.018</td>
<td>0.023</td>
</tr>
<tr>
<td>C</td>
<td>0.375</td>
<td>0.220</td>
<td>5.4x10⁻³</td>
<td>0.018</td>
<td>0.023</td>
</tr>
<tr>
<td>D</td>
<td>0.031</td>
<td>0.360</td>
<td>0.016x10⁻³</td>
<td>0.004</td>
<td>0.004</td>
</tr>
<tr>
<td>E</td>
<td>0.031</td>
<td>0.152</td>
<td>0.016x10⁻³</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>F</td>
<td>0.072</td>
<td>0.010</td>
<td>0.244x10⁻³</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>G</td>
<td>0.075</td>
<td>0.011</td>
<td>0.002x10⁻³</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>H</td>
<td>0.014</td>
<td>0.440</td>
<td>0.001x10⁻³</td>
<td>0.003</td>
<td>0.003</td>
</tr>
<tr>
<td>I</td>
<td>3.47</td>
<td>-0.07</td>
<td>-</td>
<td>-</td>
<td>0.006</td>
</tr>
<tr>
<td>Coupler</td>
<td>4.586</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.089</td>
</tr>
</tbody>
</table>

Mass and Inertia Values for the Cranks

<table>
<thead>
<tr>
<th>Element</th>
<th>Mass, M (kg)</th>
<th>d (m)</th>
<th>( I_G ) (kg·m²)</th>
<th>( Md^2 ) (kg·m²)</th>
<th>( I_{yy} ) (kg·m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.550</td>
<td>0.100</td>
<td>1.9x10⁻³</td>
<td>0.006</td>
<td>0.025</td>
</tr>
<tr>
<td>B</td>
<td>0.550</td>
<td>0.100</td>
<td>1.9x10⁻³</td>
<td>0.006</td>
<td>0.025</td>
</tr>
<tr>
<td>C</td>
<td>1.750</td>
<td>0</td>
<td>1.18x10⁻³</td>
<td>0.006</td>
<td>0.019</td>
</tr>
<tr>
<td>D</td>
<td>0.089</td>
<td>0.215</td>
<td>17x10⁻³</td>
<td>0.005</td>
<td>0.021</td>
</tr>
<tr>
<td>E</td>
<td>0.089</td>
<td>0.215</td>
<td>17x10⁻³</td>
<td>0.004</td>
<td>0.021</td>
</tr>
<tr>
<td>F</td>
<td>12.502</td>
<td>-0.105</td>
<td>-</td>
<td>-</td>
<td>0.046</td>
</tr>
<tr>
<td>Crank</td>
<td>15.530</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.157</td>
</tr>
</tbody>
</table>
4.4.1 Masses of the Links

1. The mass of each coupler = 1.116 kg or 4.586 kg with counterbalance weights.

2. The mass of each crank = 3.028 kg or 15.530 kg with counterbalance weights.

4.4.2 Mass Moments of Inertia

1. The mass moment of inertia of the coupler = 0.083 kg·m² without counterbalance weights and 0.089 kg·m² with counterbalance weights.

2. The mass moment of inertia of the cranks = 0.111 kg·m² without counterbalance weights and 0.157 kg·m² with counterbalance weights.

These results can then be used in the Bearings Analysis Programme to obtain values for the maximum torque and bearing forces.

4.5 Bearings Analysis Programme and Results

The programme can be seen in Appendix B1. It incorporates an RPA subroutine in Appendix B2. Both programmes are in Fortran, and make use of equations developed in Chapter 3. The M and I values used are slightly different from those in Table 4.1. They were derived earlier on for the unmodified links to help in the selection of the servo motors. A re-run of the programme with the new set of data was not possible as the old computer was being dismantled to make way for a new Honeywell. However the factor of safety applied in the selection is sufficient to contain the expected differences.

Portions of the results (which are based on the old data) may be seen in Table 4.3. They give the maximum values of some of the parameters of interest. The results are as follows:
<table>
<thead>
<tr>
<th>V</th>
<th>( A_x )</th>
<th>( A_y )</th>
<th>( B_x )</th>
<th>( B_y )</th>
<th>( C_x )</th>
<th>( C_y )</th>
<th>( D_x )</th>
<th>( D_y )</th>
<th>( E_x )</th>
<th>( E_y )</th>
<th>( T_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_5 )</td>
<td>TORQ</td>
<td>( R_{W_1} )</td>
<td>( R_{W_2} )</td>
<td>( R^2(2) )</td>
<td>( R^2(5) )</td>
<td>( R^1(2) )</td>
<td>( R^1(5) )</td>
<td>( R^1(2) )</td>
<td>( R^1(5) )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.136E-12</td>
<td>0.165E-02</td>
<td>0.184E-02</td>
<td>0.165E-02</td>
<td>0.189E-02</td>
<td>0.165E-02</td>
<td>0.189E-02</td>
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<td>0.189E-02</td>
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<td>0.197E-01</td>
<td>0.34E-02</td>
<td>0.197E-01</td>
</tr>
</tbody>
</table>
Torques:
The maximum torque on each crank = 58 N-m if the links are counterbalanced and 8 N-m, otherwise.

Bearing Forces:
The maximum force acting on each bearing is approximately 35N - i.e. 35N in the x-direction and 0.0047N in the y-direction.

Crank speeds:
The maximum value for R1(2) is 0.0582. This means that
\[
\frac{dR(2)}{dt} = \frac{dR(2)}{dv} \frac{dv}{dt} = (0.0582)(2\pi) \text{ rads/sec for the 250 mm dia circle}
\]
= 3.50 rpm
or
\[
(0.0582)(20\pi) \text{ rads/sec for the 25 mm dia circle}
\]
= 35.00 rpm

4.6 Bearings Selection
The ideal situation would be to have frictionless joints, but this being impossible, standard bearings are recommended. Deep grooved ball bearings are usually the best choice if a system is lightly loaded. For applications requiring heavy loads, roller bearings are more appropriate. The use of either type of bearings presupposes that there is good alignment between the housing and the shaft. Otherwise self-aligning ball bearings or spherical ball bearings are to be preferred.
Although the coefficient of friction in these bearings varies with speed, load and lubrication, yet a value can be chosen which is applicable to normal operating conditions and favourable lubrication. SKF recommends a coefficient of friction value of 0.0013.

Thus for an unloaded RANDOMM, the maximum dynamic force at each joint, as given in Section 4.5, is approximately 35N. A method of selection of bearing sizes will be found in the same reference.

The output speed from the harmonic drive is not expected to be above 40 rpm. For such a slow speed as this, SKF recommends that the value of the Basic Static Load Rating, $C_0$, be used in selecting bearing sizes. Static Load Ratings derived from static forces acting at the various joints of the mechanism are as follows:

- Output point: 454N
- Coupler-crank joint: 500N
- Crank-frame joint: 652N

These values are relatively small, and selection of SKF 618/8, 618/8 and 61801 could have been made, but due to pin sizes and provision for use of higher loads, selection became based on sizes of the pins. These were

- SKF 6001 ($C_0 = 2240N$) for output points
- SKF 6201 ($C_0 = 3100N$) for coupler/crank joints
- SKF 16004 ($C_0 = 3400N$) for the frame joints.
4.7 **Springs Selection**

Several factors contribute to positional inaccuracy. Some of these are:

1. System vibration (already mentioned)
2. Wear in the various bearings
3. Backlash in joint bearings
4. Manufacturing errors and tolerances
5. Backlash in gearing

One of these, backlash, is inherently present at all joint bearings, so provision must be made to control it.

A method suggested for RANDOMM, is to attach a suitable spring to connect each crank to the adjoining coupler. The springs serve the purpose of ensuring that the bearings are in constant contact with the shafts or pins during operations. Recommended spring attachment points should be located 80 mm from joints B and D along the coupler and crank (Figure 4.4).

Whether springs are needed or not depends on whether impacts occur at the bearings. This subject has been studied by Fawcett and Burgess\(^\text{10}\) and by Earles and Wu\(^\text{11}\). It is not possible to use such forecasts for RANDOMM because it is not known, in advance, the trajectory that will be required for point C.
PLATE 1: Complete view of mechanism
4.8 The Rig

It was decided that the mechanism be mounted in a cage-like type of rig. An additional requirement of making the rig mobile became necessary for reasons of easy transportation to and from prospective customers. Plates 4 and 5 show the production drawings of the cage. There were, however, other design requirements.

4.8.1 Design Considerations

It was decided that:

1. The rig should provide a rigid mounting for both the actuators and the mechanism.

2. The design should ensure that the frame pivots are truly in a horizontal or vertical plane (depending on the mode of loading) during operations.

3. It should be possible to operate the mechanism when placing the rig on any three of its sides. This requirement follows from the fact that the mechanism itself must be tested in its three loading modes.

4. The rig must carry an apparatus for recording the output paths of point C of the mechanism.

5. The mounting must satisfy national safety standards.

6. The entire system should be light enough to be carried by two persons.
4.8.2 Mounting of the Drive Components

It was convenient to use hot finished seamless steel tubes of square sections for the construction of the rig, but in order to ensure smooth operation of the system, it was necessary to determine approximately the natural frequency of the framed structure for comparison with the speeds of the servo motors. As will be seen later, the means of determining the moment of inertia of the structure or parts of it, is based on very rough assumptions with regards to the cross-sections of the systems (Figures 4.6(c) and 4.7(c)) and the way they are loaded. But it was considered quite important to undertake the determination, as a means of having a working basis for the selection of the steel section for the rig.

A square tube of size $30 \times 30 \times 3.2$ mm was selected and deflections were tested in two directions. Loading configurations and their idealized beam representations are given in Figures 4.6 and 4.7. In both figures, the maximum force induced by the mass of the mechanism, the mass of the attached load at C ($= 445$ N) and its induced centripetal force in the direction of the load, is 862N. Forces induced on the beam by the harmonic drive and the motor/tacho unit are put at 85N and 140N respectively. For the chosen square tube, its weight per length is put at 27N approximately.

In Figure 4.6, the equivalent beam is made up of three lengths of the square pipe. The mechanism's crankshaft is assumed as
forming a continuous extension to the two bars on which the drive components are mounted. The total length of the equivalent beam is the distance between the two levelling screws. The beam is considered as simply-supported with length equal to 0.88m (1.004m in the transverse direction). As would be observed only one half of the system is considered in this view. The other half is identical.
(A) Loading of the system

\[ W_1 \quad W_2 \quad W_3 \quad W_4 \]

(B) Equivalent beam

(C) Idealized cross-section of (A)

\[ I \]

\[ x_1 \quad x_2 \quad x_3 \quad x_4 \]

\[ y \]

\[ 4.5 \text{ cm} \]

\[ 4.5 \text{ cm} \]

\[ 10 \]

\[ 4.51 \]

\[ \text{FIGURE 4.6} \]
Explanatory notes for Figure 4.6:

Each beam is a hot finished seamless steel tube: \((30 \times 30 \text{ mm, } t = 3.2 \text{ mm, } 2.65 \text{ kg/m})\)

Area moment of inertia of section \(= I = 4 \text{ cm}^4\)

Area of each section \(= 3.38 \text{ cm}^2\)

\(W_1\) is the force induced by the servo motor/tacho/encoder group of components and their mounting bracket and is equal to 140N.

\(W_2\) is the force induced by the mass of the beam (which is considered uniform) and is equal to 75N.

\(W_3\) is the force induced by the harmonic drive and its mounting bracket. It is equal to 85N.

\(W_4\) is the maximum force due to the mechanism, an attached load of 445N, and a possible centripetal force induced by this load. It is equal to 862N.

\(I\), for the equivalent section \(= 255 \text{ cm}^4\).
(A) Loading of the system (transverse direction)

(B) Equivalent beam

(C) Idealized cross-section of (A)

FIGURE 4.7
Explanatory notes for Figure 4.7:

$W_1$, $W_3$ is the force induced on the beam by mass of the drive components, harmonic drive, mounting brackets and the two square sections on which they are mounted. It is equal to 225N.

$W_2$ comprises the force due to the mechanism's group of components and the force due to the mass of the equivalent beam. It is equal to 862N.

The moment of inertia of the equivalent beam = 290 cm$^4$.

\[ a = 27.7 \text{ cm} \]
\[ b = 82.7 \text{ cm} \]
\[ c = 50.2 \text{ cm} \]
\[ d = 50.2 \text{ cm} \]
\[ e = 82.7 \text{ cm} \]
\[ f = 27.7 \text{ cm} \]
\[ l = 100.4 \text{ cm} \]
In both figures the equivalent beams have more than two loads mounted on them. For the determination of their natural frequencies, Rayleigh's principle of determination of an approximate fundamental frequency of a structure is adopted. Referring to Figure 4.6:

\[ \delta_1 = \delta_{11} + \delta_{12} + \delta_{13} + \delta_{14} \]  

\[ \delta_2 = \delta_{21} + \delta_{22} + \delta_{23} + \delta_{24} \]  

\[ \delta_3 = \delta_{31} + \delta_{32} + \delta_{33} + \delta_{34} \]  

\[ \delta_4 = \delta_{41} + \delta_{42} + \delta_{43} + \delta_{44} \]  

\( \delta_i \) is the total deflection at \( x_i \) due to all the loads acting on the beam.

\( \delta_{ij} \) is the partial deflection at \( x_i \) due to load \( W_j \) (\( i = 1, 2, 3, 4; \ j = 1, 2, 3, 4 \)).

The deflection at any point \( x \), due to a concentrated load \( W \) at distance \( a \) and \( b \) from both ends, can be determined from the equation:

\[ y_x = \frac{W b x}{6EI} \left( \frac{x^3}{2} - x^2 - b^2 \right) \]  

The following formulae were obtained for \( W_1 \):
\[ \delta_{11} = \frac{W_1 \cdot ab}{6EIx} \left( z^2 - b^2 - a^2 \right) \]

\[ \delta_{12} = \frac{W_1 \cdot ad}{6EIx} \left( z^2 - d^2 - a^2 \right) \]

\[ \delta_{13} = \frac{W_1 \cdot af}{6EIx} \left( z^2 - f^2 - a^2 \right) \]

\[ \delta_{14} = \frac{W_1 \cdot ah}{6EIx} \left( z^2 - h^2 - a^2 \right) \]

Similar results were obtained for the other loadings. These yielded the final values:

\[ \delta_{11} = \frac{0.981}{EI} \]

\[ \delta_{12} = \frac{1.262}{EI} \]

\[ \delta_{13} = \frac{1.253}{EI} \]

\[ \delta_{14} = \frac{0.531}{EI} \]

\[ \delta_{21} = \frac{0.676}{EI} \]

\[ \delta_{31} = \frac{0.761}{EI} \]

\[ \delta_{41} = \frac{3.268}{EI} \]

\[ \delta_{22} = \frac{1.065}{EI} \]

\[ \delta_{32} = \frac{1.206}{EI} \]

\[ \delta_{42} = \frac{5.644}{EI} \]

\[ \delta_{23} = \frac{1.064}{EI} \]

\[ \delta_{33} = \frac{1.206}{EI} \]

\[ \delta_{43} = \frac{5.681}{EI} \]

\[ \delta_{24} = \frac{0.491}{EI} \]

\[ \delta_{34} = \frac{0.560}{EI} \]

\[ \delta_{44} = \frac{18.097}{EI} \]
and

\[ \delta_1 = \frac{5.686}{EI}, \quad \delta_2 = \frac{9.177}{EI}, \quad \delta_3 = \frac{9.204}{EI}, \quad \delta_4 = \frac{5.087}{EI} \]

By Rayleigh's principle, the fundamental frequency

\[ \omega = \sqrt{\frac{\sum W_y}{\sum W_y^2}} \text{ rad/sec} \]

\[ = 1.271 \sqrt{EI} \text{ rads/sec} \]

\[ = 148 \text{ osc/sec} \]

In the transverse section of the rig, loading is as shown in Figure 4.7. Using the data and nomenclature given

\[ \delta_1 = \delta_{11} + \delta_{21} + \delta_{31} \]

\[ \delta_2 = \delta_{12} + \delta_{22} + \delta_{32} \]

\[ \delta_3 = \delta_{13} + \delta_{23} + \delta_{33} \]

With the same deflection equations,

\[ \delta_{11} = \frac{2.477}{EI}, \quad \delta_{12} = \frac{3.527}{EI}, \quad \delta_{13} = \frac{2.113}{EI} \]

\[ \delta_{21} = \frac{13.511}{EI}, \quad \delta_{22} = \frac{18.174}{EI}, \quad \delta_{23} = \frac{13.511}{EI} \]

\[ \delta_{31} = \frac{2.113}{EI}, \quad \delta_{32} = \frac{3.527}{EI}, \quad \delta_{33} = \frac{2.477}{EI} \]
giving $\delta_1 = \frac{18.101}{EI}$, $\delta_2 = \frac{25.228}{EI}$, $\delta_3 = \frac{18.101}{EI}$

$\omega = 0.648 \sqrt{EI}$

$I = 290 \times 10^{-8} \text{ m}^4$

$\therefore \omega = 0.648 \sqrt{2100 \times 400}$

$= 80.5 \text{ osc/sec}$

The maximum motor speed is 3650 rpm

$= 61 \text{ osc/sec}$

From the results above, the rig should have sufficient rigidity to avoid a resonance situation. It was not considered necessary to determine how stiff the supports and the crankshafts were in torsion. Both are visually very stiff and forces that would set up torsion are relatively small.

4.8.3 Levelling

It is essential that the mechanism be truly vertical, or horizontal, when in operation. A means of ensuring this, is to stand the rig on levelling screws and create a level surface on which a spirit level may be mounted while levelling adjustments are made.
4.8.4 Safety Provisions

In accordance with national safety requirements, provisions are made for all outer sides of the cage, especially areas under which there are moving parts, to be covered with wire mesh.
CHAPTER 5
DESIGN OF THE CONTROL CIRCUIT

Optimization of the displacement and speed of RANDOMM mechanism's output point depends on several factors (see Section 4.6). Two of these, backlash in the speed reducing component and the efficiency of the control circuit, are dealt with in this Chapter. Guidance is given to the reader on reasons for the selection of each component of the control circuit, and in most cases a brief theory underlying their choice and a reference to pertinent information on the component are given as well.

A closed loop control system is chosen. For the drives, a servo motor with fast response to changes in speed and direction is recommended. A schematic of the layout of the circuit is shown in Figure 5.1.

5.1 The Closed Loop Servo System

A dynamic system such as this is bound to have such system variables as load, torque and amplifier gains. A closed loop control system has the advantage (in comparison with an open loop system) of not being sensitive to variations in these parameters. It performs correctly despite their presence in the circuit. But mere provision of a closed loop system is not all there is to control. The circuit itself must remain stable at all times. This means that the circuit must include components that ensure this stability.
FIGURE 5.1
SCHEMATIC OF THE SERVO CONTROL SYSTEM

notes
ENC - Encoder
DAC - Digital-to-analogue converter
Four types of servo control are available. These are position, velocity, torque and the hybrid control modes. The one selected for this work is the position control mode since we seek to control the positioning of point C.

In this mode, the controlled variable is the position of the motor shaft. Figure 5.2 shows a block diagram of the system. The work of the velocity feedback loop in the diagram is to increase the stability of the system and to control its response to the changing speed of the motor shaft.

FIGURE 5.2
Electrocraft\textsuperscript{12} gives details of the transfer functions of the two loops. The reader is advised to examine the case for the hybrid control mode. It may become necessary in future applications of RANDOM\textsuperscript{MM} mechanism to apply this system of control in place of position control. Electrocraft\textsuperscript{12} also gives details of the hybrid control mode. Kuo\textsuperscript{13} also has detailed information on the various control modes.

5.2 Components of the Control Circuit

Referring again to Figure 5.1, each circuit consists of a harmonic drive for speed reduction, a printed armature DC servo motor, a tachogenerator, an optical incremental encoder, a digital-to-analogue (DAC) converter, a servo amplifier, a microcomputer with a tape reader and the DAC- and Encoder-microcomputer interface boards. The decision to adopt the particular makes of the various components was based either on availability or on the fact that the same makes of components were successfully used elsewhere for similar purposes.

Each of the components is introduced below, but the reader is advised to update information as new or modified products frequently replace older ones. Product sources include: Acutronic Ltd, Small Electric Motors (SEM) Ltd, Inland Motors Ltd, Unimatic Engineers Ltd and HMK Services Ltd.

It was estimated in Chapter 2 that the cost of the system would be about £3500. Table 5.1 shows details of costs. The estimated value may be reached if the cost of the microcomputer system is added.
## TABLE 5.1

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<td>B. Encoders</td>
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**TOTAL:** £2372
5.2.1 The Speed Reducing Component

The Harmonic Drive was chosen as a speed-reducing component of the control circuit. It consists of an internally toothed elliptical wave generator in mesh with an externally toothed 'flexspline' which is machined from a thin walled flexible steel cylinder. A single-view diagram of the drive is shown in Figure 5.3. The wave generator is driven by an eccentrically-fitted ball race to produce a high drive efficiency. When the wave generator is given a drive the flexspline is deflected into the circular spline and the output is taken from the flexspline.

The reduction ratio is given by the expression, \(\frac{T_f - T_c}{T_f}\).
where $T_f$ is the number of teeth on the flexspline, and $T_c$ is the number of teeth on the circular spline. The ratio gives a negative result since $T_c$ is always greater than $T_f$.

The drive offers reduction ratios of the range 78:1 to 320:1. A light and compact component, it withstands high torques (of the order of 5840 N-m), low backlash (less than 8.5 minutes of arc for standard units and 3 minutes of arc for optimised units). Additional information on this can be obtained from Harmonic Drive\textsuperscript{14}.

From the results of the bearing analysis in Chapter 4, the maximum value of the crank speed is 3.66 rads/sec or 35 rpm. For a motor of rated speed equal to 3650 rpm (see Section 5.2.2) the required gear ratio is approximately 100.

5.2.2 The Servo Motor

Currently-existing Servo Motors are of the DC and AC types and of speed range 2700-4000 rpm. The different types are listed in Section 2.4. A quick guide to their selection may be seen in Appendix C and a detailed guide in reference 12.

The choice of the servo motor type depends more according to Electrocraft\textsuperscript{12}, on guess work than on analysis. The selection of the motor type, the printed armature servo motor, for this work was based on an educated guess. A Leicester Polytechnic research group which was working on a similar system found the motor quite satisfactory.
The motor selected for this work is the G12M4 from Printed Motors Ltd. It has a nominal voltage of 48V, rated current 4.4 amps, rated speed 3650 rpm and rated torque of 55 oz in (3.88 N-m) and a pulsed torque of 1200 oz in (8.46 N-m).

5.2.3 Tachometer Generator (Tacho)

A position-control servo system must have a speed feedback loop to make the system stable. The transfer function of this loop is provided by the tacho.

Essentially the tacho generates and outputs a DC voltage which is proportional to the motor shaft speed. The tacho does not provide any significant power of its own. The transfer function, or the relationship between the output voltage of the tacho and the speed of the motor shaft, is linear.

5.2.4 Shaft Encoders

A shaft encoder provides the most efficient method of sensing the position of a rotating shaft. It converts a continuous variable to a chain of discrete, digitized quantities and outputs them in TTL-compatible form for easy reading by a microprocessor. In effect, it is an analogue-to-digital converter.

There are two main types: the absolute and the incremental. Both are popularly used in control circuits of industrial robots and NC machines. The former is most used in position control while the latter is best in speed control.
According to Litton\textsuperscript{15} 16-bit models of absolute position encoder are available and counts of the order of 86400 per revolution are possible. Reading of shaft positions is achieved by use of the Moire fringe system, in which light passes through a grid which is cut through a disc, to a photo-transistor. This gives out a sinusoidal output which is changed to square waves by a Schmidt-trigger. The waves are amplified to give clear output signals. The discs are made from laminated plastic (on grounds of low inertia, costs, and excellent resistance to shock and vibrations); the lines on the discs are produced by a photographic process. A more detailed description can be obtained from the catalogues of some encoder manufacturers.

The optical shaft incremental encoder has two discs with equal sets of lines but phase-shifted by 90\degree. This effect enables direction to be detected as an up/down or backward/forward motion. The square waves produced are output serially. Where required, a zero marker pulse can be incorporated into its design to give one pulse per revolution count, for special position reference. In combination with an external counter it can replace an absolute encoder. So, in effect, the choice between the two lies in the cost trade-offs of the system.

The AIM 65, with an 8-bit data bus, can handle conveniently, a maximum of two-byte subtraction. Thus each sample reading from the encoder may be taken in two 8-bit words. This is the reason for the use of four 4-bit counters on the encoder boards. It also means that the maximum reading of FFFF (hex) (or 65535 decimal)
from the board can be made to correspond to our maximum crank angle of 1.25 radians. With a gear ratio of 100, the encoder's maximum counts per revolution can be set to a value equal to 
\[(65535 \times 2\pi)/(100 \times 1.25)\] or 3294.

Partly due to our policy of minimum cost and partly because there was no certainty as to what the maximum error value to be output to the 12-bit digital-to-analogue converters would be (this error must not exceed 7FF (hex) or 2047 (dec)), a decision was taken to use a 256-count optical incremental encoder. From the results of tests, it might become necessary to replace the encoders with those with larger count values. There are absolute models with counts of the order of 86400 and lower per revolution, according to Litton15. There are also standard incremental models with counts in the region of 2540 and lower, according to HMK16.

5.2.5 The Digital-to-Analogue Converter (DAC)

The DAC converts a digital input from a microprocessor to an analogue output voltage (or current in some applications) for driving the related device. A detailed description of the working of a DAC, and definitions of associated errors are given by Jaeger17. He recommended 8-, 10-, 12- and 14-bit resolution DAC's as the most economical. Those with higher resolutions (16-, 18- and 20-bits) give difficult precision. Our choice of a 12-bit resolution DAC depended more on empirical results from the Leicester Polytechnic project. It is expected to give
a less-coarse operation than an 8- or 10-bit DAC, especially considering the large (rated) voltage needed to operate the motor.

In this project the Hybrid DAC (model 9349-12) was selected. It has a maximum settling time of 15 μs. It is used in the bipolar mode. The input code is the offset binary (with 1111 1111 1111 designating (+ Full Scale - 1LSB) volts, 1000 0000 0000 designating 0 volt and 0000 0000 0000 designating (- Full Scale Voltage). The input reference voltage is ±15 volts.

5.2.6 The Microcomputer (MPU)

'MPU' is actually the abbreviation for "microprocessor unit" but is used throughout this work to designate both the computer and the processor. Books on the theory and applications of the microcomputer abound everywhere. At present there are a great variety of microcomputers on the market - so great that the choice of one over the other becomes extremely difficult.

Any standard MPU would serve our purpose, but the best microcomputer in terms of software handling is one with 16-bit data buses, 16-bit accumulators and registers. An additional advantage exists in using an MPU which has at least two 16-bit ports and one control port. The 6809, Intel 8085, Altos 68000 are a few of the various types that possess this capability.

In this work the Rockwell AIM 6502 on grounds of availability, is used. It has 8-bit data bus, 8-bit ports, 8-bit accumulators and registers and a sufficiently large memory (36K). It can
accept a low level language programme as well as a high level language (Basic) programme. Unlike the Pet, Apple or Atari, into whose class the AIM also belongs, its software capabilities are very limited. Programming is therefore more laborious, though more educative.

5.2.7 The Servo Amplifier

This module is of the Hauser make and consists, in the main, of:

a) the circuitry of the operational or power amplifier, N59, which determines the servo control action, see Appendix D.
b) a potentiometer, R3, for adjusting speed. (The maximum speed is obtained by setting R3 to its maximum value and adjusting R65 (and R27 if necessary)).
c) amplification control parameters, and
d) pulse width modulator which converts the DC voltage generated by the servo control unit into digital values necessary for the final output stage.

Together with the DC motor, tachogenerator, a mains supply transformer and a current-smoothing choke, the servo-amplifier forms a single drive unit with which to control rotational speed. The electrical component needed to regulate the motor is fitted in the circuit.

Figure 5.4 shows how the different components are connected to the regulator circuit terminals. Hauser gives details.
5.2.8 Power Supply Unit

Power is supplied to the circuits from a single-phase 250V, 13 amp mains socket through a pair of transformers (and chokes). The transformer's secondary leads are connected directly to the servo amplifier terminals, Figure 5.4, for subsequent supply to all the other components of the circuit. Supply to the encoders (5V) was taken from the microcomputer terminal.
5.3 Interfacing Control Circuits to the MPU

Each of the two control axes is connected to the MPU through a pair of interface cards - one interfacing the MPU to the circuit through the DAC, and the other interfacing the encoder to the MPU. Access to the DACs and encoders must be made in 8-bit and 5-bit data buses.

Plates 6 and 7 show the two interface cards. Brief descriptions of the methods used follow in the next sub-sections.

The reader is referred to Appendix E for the various pin connections.

5.3.1 The DAC-MPU Interface Card

According to Jaeger a number of DACs now exist in single chips on the market, complete with data latches at the input and an address decoding circuitry to help the MPU address the DAC. However, failure to lay hands on one, prompted the use of a custom-built one from Leicester Polytechnic.

The 74LS 138 is a 3/8 decoder used to demultiplex data through the dual-in-line (dil) switch. The active-high enable input 'E3 (or G1) is held high while E2 (or G2B), one of the two active-low enable inputs, is routed to ground. The other E1, (or G2A) is connected to the MPU by the b16 data line for programming purposes. The 74LS 138 outputs a low level (\( \bar{u} \)) pulse.

The three binary select inputs pins 1, 2 and 3 (or A, B and C) are connected to the MPU by the b17, b18 and b19 data lines, for programming purposes. When the b16 line is kept low,
control data is routed through the di1 switch. When high it serves as a data inhibit input. For example, the select inputs "000 and 001", direct control across pins 1 and 5 of the di1 switch onto the dual monostable multivibrator. The setting of the 74LS 221 is:

- C1r (rq) high level pulse
- 1A (+) negative transition
- 1B (r-)

This setting outputs a high level pulse of width 50 ns out of 1Q (pin 13) and a low level pulse of the same width out of 1Q (pin 4) during the negative transition of the triggered input from 1A (pin 1). The stability and width of these pulses are controlled by the external timing components (the 10 μF capacitor and the 10K resistor).

The 1Q output leads on to the 74LS 175 latch which is positive-edge triggered, to strobe in data from the 4-bit data bus coming out from port A of the MPU. This data also appears, subsequently, on the input data bus of the connected 74LS 174. Meanwhile 1Q (which is a low) puts the RS-type flip-flop (74LS 74) into the PR (or S) high, C1r (or R) low mode, but that input stays, awaiting a "\(^{\uparrow}\)" from the clock.

Next, the control lines are set in the "001" mode to direct a low pulse across pins 5 and 12 of the di1 switch to the monostable which now triggers a high pulse (setting: 2 C1r, 2Bn, 2A+) from the negative-going edge of the high input pulse from
"2A (pin 9), out of 2Q (pin 5). Pulse width is also 50 ns. This pulse is fed into the D-type octal latch 74 LS 373. With control at low (pin 1) and E (or G), pin 11 at high, data is strobed into the latch from the 8-bit data bus. Both sets of data (the 4-bit and the 8-bit) now appear at the inputs of the two 174's. Meanwhile the low from 2Q to the clock latches the output high that was set up previously, onto the two 174's for final spontaneous transfer of all 12-bits to the DAC.

The DAC converts the binary weight of the input into a proportion of the reference voltage and outputs that analogue value to the operational amplifier.

5.3.2 The Encoder-MPU Interface Board

The two encoders are optical incremental types and so the interface card must consist of not only a system of latches as in the DAC but also of counting the pulses and of sensing the direction of rotation of the motor shaft. Plate 7 shows the card.

The di1 switch, S1 RS-337526, is used to direct encoder signals unto the rest of the circuit. The 220 Ohm resistors ensure that only the high data go through to the rest of the circuit. Line A and line B are identical except for the 90 degrees phase difference between them. The first pair of inverters (U1's) convert the high data to low. The 270 Ohm resistors in combination with the 0.01F capacitances constitute low-pass filters meant to absorb any ripples. The next pair of inverters
re-convert the signals to 1's. At this point the signals have to be differentiated for direction sensing.

Figure 5.5(a) shows the effect of combining two equal signals A and B (period T) to obtain the resultant signal, C.
C is of double length when compared to A or B. The relationship which exists between the peaks and troughs of the two sets of square waves is used to detect the direction of rotation of the motor shaft. The output signal C is configured in Figure 5.5(b) as a clockwise rotation of shaft if the signal is read from left to right and anticlockwise if read from right to left. When dealing with square waves it is necessary to distinguish between the two pairs of surfaces viz the high and the low and the leading and the trailing edges. This is achieved by use of an inverter or a monostable or a combination of both. The effect of this distinction produces a wave $C'$ shown in Figure 5.5(a). There are four of these short pulses per period of A or B. Each pulse may be distinguished as:

a) $A+.\overline{B}$
b) $B+.A$
c) $A+.B$, and
d) $B+.A$

Reading the signal in the sequence above gives the clockwise direction. Figure 5.6 shows the above sequence and the sequence for the counterclockwise direction. In the latter, the signals are read from bottom to top. Each pair above is input into a NAND gate, U4 or U5. The first four NAND gates read the output signal from left to right, whereas the next four read it from right to left. The former forms the four inputs into the first AND gate, and the latter those of the second AND gate. When all input bits show 1's a pulse is output by the gate. These are
\[ t = \text{transition from low to high} \]
\[ f = \text{transition from high to low} \]
\[ \text{ills} = \text{one low-level pulse of A/B} \]
\[ A/B = \text{one high-level pulse of A/B} \]
\[ \text{Cl~} = \text{clockwise} \]
\[ \text{CCW} = \text{anticlockwise} \]
\[ \text{denotes NAND gating} \]

**FIGURE 5.6**

Notes:

\[ + = \text{transition from low to high} \]
\[ - = \text{transition from high to low} \]
\[ \overline{A/B} = \text{one low-level pulse of A/B} \]
\[ A/B = \text{one high-level pulse of A/B} \]
\[ \text{CW} = \text{clockwise} \]
\[ \text{CCW} = \text{anticlockwise} \]

---

denotes NAND gating

**FIGURE 5.6**
led out to the counters for conversion into 16-bit parallel outputs.

A method similar to the one used in the DACs is used for latching the outputs. Since the clock of the flip-flop U7 is always high, any information from the pins 4 and 1 will immediately be output. If the Clr goes high first before the "PR", the green led lights, to show that signal 'B' leads signal 'A', or an increment. If the preset goes high first before Clr goes high, 'A' leads 'B' and the yellow led lights.

The 3/8 decoder, U17, demultiplexes data from control lines b17, b18, b19, enabled by b20, to direct control through the dil switch settings for the latchings of the least significant 8-bit data, and later, the most significant 8-bit data.

Finally, the resetting of the two sets of red leds is done both manually, by a push button, or by programming, using the b29 and b30 control lines to the dil switch labelled '52' in Plate 7.

5.3.3 The Control Lines

In the project, port B of the MPU is configured wholly as a control port. Figure 5.7(a) shows this configuration, while Figure 5.7(b) shows the dil switch settings.

All four components (the two DAC's and the two encoders) share the same control lines (bits 0, 1 and 2 of port B). Bit 3
serves as output bit for the enable line to the two encoders while bit 4 is the output bit of the enable line of the two DAC's. Individual DAC's and encoders are then further selected by programming the first three bits.

The dil switch settings are accessed as follows:

i) Codes 000' and 001 of the control lines direct control data through the Y0/Y1 setting.

ii) Codes 010 and 011 direct data through the Y2/Y3 setting.

The use of these settings for programming is discussed in Chapter 6.
5.4 Brief Review of the Control System

Referring to Figure 5.1, data is read from the encoder - first the eight LSB and then the five MSB - into the MPU through port A for comparison with the command position data stored in the data tables in the MPU memory. The error is output to the DAC's. The selection of the DAC's is done by related control data from port B. Details of this selection can be found in the programmes in Chapter 6. The DAC then sends out an analogue voltage, equivalent to that data, for amplification by the op amp. The amplified voltage is then routed to the motor. As the motor shaft turns, the tachogenerator outputs a voltage proportional to its speed to the summing junction of the controller for the control of system stability. The encoder reads the absolute position of the motor shaft for input into port A of the MPU.

The motor speed is reduced by the harmonic drive (ratio 100:1) for the drive input to the mechanical load. A cycle of the various processes in the control system is completed when the above steps have been carried out for both drive axes, A and B.
CHAPTER 6
SOFTWARE DEVELOPMENT

This chapter develops software methods for the control of the motions of the mechanism. A high level language constructs digital representations of the crank angles and stores them as data sequentially in tables in the MPU memories. A low level language then uses them to manipulate point C of the mechanism along the predetermined paths. Hard copies of both programmes are given in the text, while relevant portions of necessary print-outs are given in the Appendix. In a dedicated use, these languages will be stored in EPROMs in the MPU.

Writing of software programmes can take as much time, or more, as the design of the hardware. This phase of the work involves a thorough understanding of the architecture of the MPUs Versatile Interface Adapter (VIA), input/output handling and a general understanding of the working of the microcomputer itself. These areas of study are covered by Scanlon19, Raeto20, Zaks21 and Rockwell22.

The software requirement for this phase of the work consists of moving the output point of the mechanism from a park position, P to a start position S and, after a brief stop, getting it to move along the periphery of the specified area five times at any desired speeds or less than 1 cycle per second, and finally bringing it back to the park position.
6.1 Graphical Configuration of the System

A diagram showing the system for which the software development is made, is shown in Figure 6.1. As in Chapter 3, ABCDE is the 5-bar linkage with point C as the output point. The nomenclature in the sketch are those used in the high level language programme.

6.1.1 Definitions of Specific Positions:

First, there are the two frame pivots A(XA, YA) and E(XE, YE) which are assigned the points A(0,0) and E(45.1, 0). Second, there is the fixed centre of the maximum circle, F. This is given the value F(22.55, 44). Third, there is the park position of the mechanism. This occurs when the 5-bar linkage takes up the position ABp P Dp E. Point P is assigned the value P(22.55, 20). This position is only slightly higher than the optimal minimum allowed for the mechanism due to the value of its transmission angles. At this position crank angles A2 and A5 have their limit values.

Two microswitches are set on the frame to these two positions to check on further downward motions of the cranks and thereby give the system a fail-safe characteristic.

6.1.2 Description of Desired Motions

As will be recalled, Point C is to trace any path within our maximum circle. Its movement from P to S1 may be done in any fashion. One way is to move it along a straight line from P.
S1, S, P refer to points on the X-Y plane.
S1 refers to any start position.
FS1 is a vector (magnitude R1, direction T1)
Nomenclature for Joint Positions, Link Lengths and Angular Positions of the links are as stated in Figure 3.1.
PS is a straight line path (shown in dashed line).
F is the centre of the maximum circle which is also shown in dashed lines.

FIGURE 6.1
In others, it may be convenient to move it vertically first before turning in the direction of S1.

The vector F51 is given the magnitude R1 cm and T1 radians direction. For the maximum circle, S1 = S(35.05, 44), R1 = R = 12.5 cm and T1 = 0. If N is an arbitrary number that divides the circle into an equal number of units, then T1 may be increased in unit steps, I, where I = 0, 1, 2, 3, ..., N. Thus the value of T1 at any instant will be \( \frac{2\pi}{N} \times I \) radians. Used with the equations in Section 3.1.2, the various values of X, Y, A2, A3, A4, A5 can be obtained.

6.2 Construction of X-Y Position Command Data Tables

Referring to the programmes in Chapter 3, it will be observed that it takes a long time for the computer to execute the various calculations of crank angles. Even if the programme is written in a low-level language (and that would take quite a lot of time to do), point C will not be able to move in real time. The strategy usually adopted in circumstances such as this, is to do all these calculations in a high level language and store all relevant data in the memories of the MPU. That way the MPU merely accesses the tables to "peek" out the calculated values at the appropriate time. This peering takes no longer than a few microseconds to execute. It is for this reason that these data tables are to be constructed. The rest of the section contains the necessary tools for this construction. Reference should be made to the flow chart in Figure 6.2 and the data logger programme in Figure 6.4.
6.2.1 Conversion of X-Y Positions to Crank Angles

The mechanism, it will be recalled, is considered in its Mode 1 configuration. The equations for the conversion of the X-Y positions to crank angles are given in sub-section 3.1.2. Each x-y positioning of point C corresponds to a unique pair of angles for the two cranks. The angles are in radians, and as in Chapter 3, have a maximum and a minimum value. This part of the programme is covered by subroutine 2 (see flowchart) and lines 450-545 of the Data Logger.

The angles are read by the MPU via the harmonic drive, the servo motor and the encoder. The values must be read in their digital formats - which are given by the encoders.

6.2.2 Conversion to Encoder Counts

Each encoder makes 256 counts per revolution of the motor shaft. With a gearing ratio of 100, each complete revolution of the crank would produce 100 revolutions of the motor shaft and consequently 25600 counts of the encoder. A fraction of a revolution X, therefore produces \( (25600 \times X/2\pi) \) encoder counts. This value equals 4074X approximately.

For the P-S motion of point C, the largest variation in the angular position of the crank (see sub-section 3.2.3) is 1.052 radians, but in the tracing of the maximum circle this variation is 1.254 radians. Using the latter value as the maximum value of X, the highest value of encoder counts is calculated as 5110 approximately. This converts to 13F6 hexadecimal.
value. So encoder readings must be read in two-byte units -
which means 13 or 16-bit positions. At this stage, it is to be
accepted in good faith that the expected error signals will not
exceed the 11-bit space allocated to it in the DAC (the 12th bit
space being reserved for the polarity of the data).

6.2.3 Movement From Park to Start Positions

For the purpose of programming, the general start position
is to be henceforth designated as (XS, YS). So,

\[
\begin{align*}
XS &= Rl \cos Tl + XF \\
YS &= Rl \sin Tl + YF
\end{align*}
\]

If line PS1 is divided into an arbitrary number of equal units,
M, then point C (X,Y) is defined by the equations:

1. \[ X = I \frac{(XS - XP)}{M} + XP \]
2. \[ Y = I \frac{(YS - YP)}{M} + YP \]

where \(I = 0, 1, 2, \ldots, M\). By inputting \(Rl, Tl\) and \(M\), the
movement from the park to start position will be clearly defined.
This part of the programme is handled by subroutine 1 (see
flowchart and the programme).

6.2.4 Movement Along the Large Circle

Point C (X,Y) is defined, for motion along the 250 mm diameter
circle by the equations:
1. \( X = R \cos \left( \frac{2\pi J}{N} \right) + X_F \)

2. \( Y = R \sin \left( \frac{2\pi J}{N} \right) + Y_F \)

\( N \) is an arbitrary number of equal units into which the circle is divided. \( J = 0, 1, 2, \ldots N \). Calculations for \( X \) and \( Y \) are handled in the programme by subroutine 7.

6.2.5 Constructing Data Tables

The AIM 65 microcomputer used here (with its RAM extension) is a 36K machine. Thus there is ample space for the construction of the data tables. The tables convert the allocated RAM's to "ROM's."

The storage of data must be sequential, according to the sense of progress of point C. Since our machine has 8-bit X- and Y-registers, it is most convenient, to build the tables in blocks or multiples of 256 (in order to conform to the counting process). Its accumulator and memories are addressable in 8-bit or multiples of 8-bit words. This calls for extra care in the assembly language programming as the crossing of a page boundary must affect the execution time of the programme algorithms.

For the Basic programme, the "poke" statement handles only decimals. So each encoder count has to be represented by two "decimal coded byte" values (abbreviated DCB), each not exceeding 255 (decimal). The conversion from encoder counts to DCB is done by subroutine 3 (see programme and flowchart). Each DCB pair of values is stored in two separate tables, as a least significant
byte and a most significant byte, to make access easy.

The data represent the commanded positions for the motor shaft. The tables will be referred to simply as "Data Tables". It is advisable to place all the tables at the bottom-most free RAMs in order to leave a continuous free RAM space above for the programmes. For this work, selection was made as shown in Figure 6.3. The layout is simple and self-explanatory. The sizes of the tables depend on the values given to M and N.
FIGURE 6.3: Position Command Data Tables

Note: One memory page is allocated to each of the four tables for the straight line path, while two pages are allotted to each of the four tables for the circular path. In our first test each table is partially filled.
START
READ ALL CONSTANTS
DEFINE ALL VARIABLES
INPUT M N, R1, T1
I = \emptyset

SRT1

PRINT X, Y

SRT2

PRINT LINK ANGLES

CONVERT CRANK ANGLES TO ENC. COUNTS

PRINT ENC COUNTS

SRT3

PRINT BYTE DEC VALUES

M = No. of equidistant points on straight line
N = No. of equidistant points on circle
R1 = Radius of circle
T1 = Start angle wrt x-axis

- Defines x, y positions on straight line path
- Works out equivalent link angles
- Recorders counters in two decimal coded byte (DCB) values
Pokes DCB values into data tables

Converts encoder counts to Hex values for easy checking

Prints HEX values

I = I + 1

Is I = M?

Yes

J = Ø

Defines X-Y positions on circular path

Prints X, Y

Prints link angles

Converts crank angles to enc. counts

Prints encoder counts

SRT 4

SRT 5

SRT 7

SRT 2

SRT 3
FIGURE 6.2: Flow chart for position data tables programme
LIST
10 PRINT "DCMF1"
15 POKE 188, 189: POKE 189, 143
16 PRINT ""
18 INPUT "NO OF STR. LINE UNIT=": M
20 INPUT "NO. OF CIR. UNITS=": N
22 INPUT "LEN FS(CM) R=": Ri
24 INPUT "START ANGLE(RADS)="; T1: PRINT ""
25 PRINT "DIGITAL CONTROL PROGRAM"
30 PRINT "RATIS FOR LINEAR N/C"
35 PRINT "FUNCTIONS"
40 PRINT ""
45 REM=PROGRAMS TO
50 REM=LOGIN DATA FILES
55 REM=OR CONSTRUCT
60 REM=ION OF SEQUENCE
65 REM=NUM TABLES
70 REM=FOR RANDOMM
75 REM=MECHANISM'S
80 REM=ZERO-START &
82 REM=CIRCULAR PAT
85 REM=H ROUTINES
90 PRINT ""
95 REM=PRINT RESULT
S
100 REM
105 PRINT "X", "Y CM"
110 PRINT "A2", "A5 RADS"
115 PRINT "A3", "A4 RADS"
120 PRINT "L", "O ENC COUN"
121 PRINT "B1", "C1"
122 PRINT "B2", "C2"
125 PRINT "N#", "N+"
126 PRINT ""
130 REM DEFINE CONS
TS/VARIABLES
135 READ L1, L2, L3, P
140 DATA 45, 1.21, 52,
144, 3, 1415527
145 READ XP, YP, XF, YF
150 DATA 22, 55, 20, 22
155, 44
153 REM DEFINE R
155 R=12.5
157 K=L2*L2-L3*L3
172 REM ARC COS FUN
175 DEF FNF(X)=-ATN
(X/SQR(X**2+X+1)), +F/2
178 REM M IS NO OF
X-Y POINTS ON PATH
179 PRINT "ZERO-STAR T\n(STR LINE)PATH": PRIN
T"
180 FOR I=0 TO I'
186 GOSUB 450
190 PRINT I'.Y1
195 GOSUB 450
200 L=INT((R2-1.695
3683)*4674+.5)
210 0=INT((R5-3347
3683)*4674+.5)
215 PRINT I', 0
220 GOSUB 550
225 PRINT A1, B1: PRIN
TA2, B2
235 GOSUB 70
245 GOSUB 600
250 PRINT N#, N#
255 PRINT "": NEXT
260 PRINT ""=
265 PRINT ""
268 REM CIRCULAR PATH
270 PRINT "RESULTS FOR"
275 PRINT "CIRCULAR PATH"
280 REM N=NO OF X-Y
285 POINTS ON PATH
300 FOR I=0 TO I
310 GOSUB 70
315 PRINT X2, Y2
320 GOSUB 450
325 L=INT((R2-1.548
65804)*4674+.5)
335 0=INT((R5-3394
43727)*4674+.5)
337 PRINT I', O
345 GOSUB 550
350 PRINT B1, C1: PRIN
TB2, C2
355 GOSUB 855
362 GOSUB 800
365 PRINT N#, N#
370 PRINT "": NEXT
372 PRINT "": PRINT
"NOW VERIFY ENTRIES"
373 END
375 REM END FOR X/Y
(STR. LINE) PATH
385 REM R1 IN CM; T1 IN RADIANS
386 REM T1 IS ANGLE MADE BY LINE
387 REM BET F:(22, 55), START POS
390 REM WITH X-AXIS
LEN R1
408 X3=R1*COS(T1)+X
F
408 Y3=R1*SIN(T1)+Y
F
410 X=XP+1*(X3-XP)/M
415 Y=YP+1*(Y3-YP)/M
420 X1=INT(X*1000+5)/1000
500 X1=INT(Y*1000+5)/1000
505 RETURN
440 S=Y/X: T=Y/(L1-X)
450 A=K+(X^2+Y^2)/2
500 A=K+(X^2+Y^2)/2
470 C=2*L2*SQR(X^2+Y^2)
480 D=2*L2*SQR((L1-X)^2+Y^2)
490 E=ATN(S): G=ATN(T)
500 A2=E+FNA(U): A5=P-G-FNA('P)
540 Z=(X^2-D-1)/L.
550 RETURN
550 Z=(X^2-D-1)/L.
560 J1=INT(L/4096)
570 J2=(L/4096-J1)*4096
585 J4=(J1+16)+1
590 RETURN
605 Z5=INT(K4/16)+2
610 Z7=26*16+Z5+16+J7
650 RETURN
700 X=R*COS(2*P)*J/N
710 Y=R*SIN(2*P)*J/N
720 X2=INT(K*1000+5)/1000
500 X2=INT(K*1000+5)/1000
550 RETURN
600 REM CONVERSION
700 M="": N="" 
710 A="0123456789A
720 B=4095
730 FOR I=1 TO 4
740 C=INT(L/W): L=L-C*W
750 D=INT(0/W): D=D-W
760 C=INT(L/W)-D=0
770 D=LEFT$(A, C+1)
780 D=LEFT$(A, D+1)
790 N=INT(M$+RIGHT$"(C$", 1)
800 N=INT(M$+RIGHT$"(D$", 1)
850 NEXTZ
860 RETURN
870 POKE28673+I, B2:
880 POKE28525+I, B1:
875 POKE29184+I, C2:
870 POKE29443+I, C1:
880 RETURN
880 POKE29696+I, B2:
890 POKE30208+I, B1:
890 POKE38728+I, C2:
890 POKE31282+I, C1:
900 RETURN
910 RETURN
Explanatory Notes on the Data Logger Programme

1. Most of the nomenclature will be found in Figures 3.1 and 6.1. Where differences occur, those in Figure 6.1 should be upheld.

2. Line 15: The AIM 65 does not calculate inverse functions. The use of these functions must, therefore, be preceded by the ATN implementation programme. This programme uses both the ATN and the ACS functions. Line 15 gives the ATN vector and the function start address 8FBD, while line 175 defines the ACS function.

3. Lines 105-125: \((X,Y)\) are coordinates of point \(C\). But these are given by \((X_1, Y_1)\) for the straight line, and \((X_2, Y_2)\) for the specified area. Both are rounded to 3 places of decimal.

4. 'L' and 'O' are encoder counts for cranks 2 and 5 respectively.

5. "B1, B2; C1, C2" are the high-byte and low-byte DCB values representing 'L' and 'O' respectively.

6. M$, N$ are the hexadecimal equivalents of 'L' and 'O'.

7. Line 155: FS1 has magnitude \(R_1 = R = 12.5\) cm.

The placement of the data in the various tables is handled by subroutines 4 and 6 (see the programme).
6.2.6 Checking to Confirm Data

This aspect of the programming is optional, but experience shows that it is very necessary in order to ascertain that the MPU behaves itself. There are two methods of doing this.

One method is to access the memory locations in the tables and peek out the DCB values. This can be done by the statement:

\[ \text{PEEK (topmost mem. location (in decimal) of the table + a \times I)} \]

where \( I = 0, 1, 2, \ldots, N \) or \( M \), and 'a' is a factor equal to 2, 4, 8, 16, ... etc. The MPU will then reprint the selected DCB values.

The second method and the one used by the writer, is to convert the encoder counts to their hexadecimal values (see subroutine 5 of the programme). A quick check is then made manually on the keyboard using the following steps:

1. Switch the AIM to Monitor Command by pressing the "L" key.
2. Press the 'M' key followed by the hexadecimal value of the selected memory location. This step displays four sequential hexadecimal values of the DCB values in the 4 locations.
3. Press the space bar as many times as desired to print sequential data (in hex) in steps of $4$.

Portions of the print-out (and confirmation of data entries) are given in Appendix F.
6.3 Considerations for the Control Programme

As mentioned earlier, the main control programme is written in Assembly language (see pages 154 to 161). Its flow chart is given in Figure 6.11. On execution, the programme is supposed to move point C of the mechanism from the Park position along a straight line to the start position S, for further movement at 1 cycle per second 5 times around the maximum circle, and return to the Park Position. The programme will later be modified to include a delay at S before motion around the circle and another delay before the final return to P. It is also necessary to have a slow start and stop for smooth operations. These extra aspects will be examined in a subsequent stage.

However, before all else, some housekeeping operations must be carried out and decisions on programming options taken.

6.3.1 Ports Configurations

The AIM 65 has only two I/O ports each having, in turn, a two-bit control port. There is also a serial port but this will not be used since we would be reading and outputting parallel words from and to the I/O peripherals. The control requirements are rather complex and cannot be handled by the two 2-bit control points. As a result, a decision was taken to convert port B (it could have been port A instead) for use for control purposes. This left port A for use for all the data handling. A schematic showing the configurations of both ports is shown in Figure 6.5. Data from the Encoders are read into the MPU from port A.
FIGURE 6.5: AIM.65 I/O Ports Configuration for RANDOMM

TABLE 6.1: Digital Identification Codes for DACs and Encoders

<table>
<thead>
<tr>
<th>Controlled Components</th>
<th>Control Bits Position</th>
<th>Hex Value:</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30 29 16 20 19 18 17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DAC A</td>
<td>1 1 0 1 0 0 0</td>
<td>$$68$</td>
<td>MSB</td>
</tr>
<tr>
<td></td>
<td>1 1 1 1 0 0 0</td>
<td>$$78$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 1 0 1 0 0 1</td>
<td>$$69$</td>
<td>LSB</td>
</tr>
<tr>
<td></td>
<td>1 1 1 1 0 0 1</td>
<td>$$79$</td>
<td></td>
</tr>
<tr>
<td>DAC B</td>
<td>1 1 0 1 0 1 0</td>
<td>$$6A$</td>
<td>MSB</td>
</tr>
<tr>
<td></td>
<td>1 1 1 1 0 1 0</td>
<td>$$7A$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 1 0 1 0 1 1</td>
<td>$$6B$</td>
<td>LSB</td>
</tr>
<tr>
<td></td>
<td>1 1 1 1 0 1 1</td>
<td>$$7B$</td>
<td></td>
</tr>
<tr>
<td>Enc A</td>
<td>1 1 1 0 0 0 0</td>
<td>$$70$</td>
<td>LSB</td>
</tr>
<tr>
<td></td>
<td>1 1 1 1 0 0 0</td>
<td>$$78$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 1 1 0 0 0 1</td>
<td>$$71$</td>
<td>MSB</td>
</tr>
<tr>
<td></td>
<td>1 1 1 1 0 0 1</td>
<td>$$79$</td>
<td></td>
</tr>
<tr>
<td>Enc B</td>
<td>1 1 1 0 0 1 0</td>
<td>$$72$</td>
<td>LSB</td>
</tr>
<tr>
<td></td>
<td>1 1 1 1 0 1 0</td>
<td>$$7A$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 1 1 0 0 1 1</td>
<td>$$73$</td>
<td>MSB</td>
</tr>
<tr>
<td></td>
<td>1 1 1 1 0 1 1</td>
<td>$$7B$</td>
<td></td>
</tr>
</tbody>
</table>
Data to the DAC's are output also from this port.

In order to direct these data appropriately, a sound digital identification of the four peripherals (2 DAC's and 2 encoders) is needed. Bit positions 0, 1 and 2 of port B are respectively connected to Selects A, B and C (or pins b17, b18 and b19) of the two 3 to 8 decoders on the DAC and Encoder boards (see Plates 6 and 7). Bit 3 is connected to the G2A pin (or 20 pin) as an Enable to the two encoders. Bit 4 is connected to the G2A pin (or pin b16) as the Enable to the two DAC's. Each decoder operates a combined DAC and Encoder pair of boards - one for axis A and the other for axis B. The final routing of control data to select either DAC A or Enc A, or DAC B or Enc B is done by the dil switches.

6.3.2 Control Codes

Figure 6.6 shows the settings for the two switches. On board pair A the dil switches are set to Y0-Y1 position while on board pair B they are set to the Y2-Y3 position. Thus it takes a combination of a decoder select, an enable select and a dil switch select to route data logically to the four boards. For the dil switch, selection to the A-axis is done using the 000 and 001 data from the first three bits of Port B. Code 010 and 011 from the three bits route data to the B-axis.

Since each data is sent out in a two-byte pair, the MSB and the LSB, eight different selections have to be made. A zero at Port B's bit position 3 enables the encoders, while a zero
at bit 4 enables the DAC's. A one in any of the two positions inhibits data. In order to place additional checks on routing errors, each data enable is followed by a data inhibit instruction. Table 6.1 gives all the details. The reader is advised to go through the various selection codes, using a TTL data book, to ascertain the authenticity of the various data, and bits nomenclature.

Finally, bits 5 and 6 of Port B are connected respectively to Clr 1 and Clr 2 (b29 and b30). Each is cleared by a '1'.
6.3.3 Sub-programme for Servo Motor Calibration

In order to ensure that data input into the DAC's produce the output voltage pattern given in the DAC catalogue it was necessary to calibrate the two DAC's. For this, a digital voltmeter was connected to each DAC's output terminals. An assembly language programme was then written to feed a pre-selected set of data sequentially into the DAC's and their output voltages were recorded. The programme for this exercise is shown on pages 136 and 137. The data are stored sequentially in look-up tables. The programme is labelled "TEST 1". It contains a sufficiently long delay to give the programmer ample time for recording the various voltages of the voltmeters. A plot of the results is given in a graph in Figure 6.7. This programme can be made part of the main programme.

As can be seen from the graph, the relationship is linear. Data, 0800 corresponds to a zero voltage and hence the motor's zero speed and position. OFFF corresponds to the maximum positive voltage of 9.99V, while 0000 corresponds to the minimum voltage of -10V. Data of the range 0800-0000 turn each motor in an anticlockwise (ccw) direction (and hence the corresponding crank in a clockwise (cw) direction). The converse applies to data of the range 0800-0FFF. Should

The mean clockwise speed of the cranks correspond to 0400, while the mean ccw crank speed correspond to 0000.
ROCKHELL RIM 85

MEMORY FOR CALIBRATION

CMD=#=0200

35

0200 AS LDA #FF
0202 BD STA #001
0205 BD STA #FF
0208 AS LDA #78
020A BD STA #001
020D BD LDA #100, Y
0210 BD STA #001
0213 AS LDA #78
0215 BD STA #000
0218 AS LDA #68
021A BD STA #000
021D AS LDA #78
021F BD STA #000
0222 BD LDA #FF00, X
0225 BD STA #001
0228 AS LDA #75
022A BD STA #000
022D AS LDA #69
022F BD STA #000
0232 AS LDA #78
0234 BD STA #000
0237 BD LDA #FF00, X
023A BD STA #001
023D AS LDA #79
023F BD STA #000
0242 BS AS LDA #65
0244 BD STA #000
0247 BD LDA #FF00, X
024A BD STA #001
024D AS LDA #7B
024F BD STA #000
0252 AS LDA #68
0254 BD STA #000
0257 AS LDA #48
0259 BD STA #000
025C AS LDA #48
025E BD STA #000
0261 BS BD PLS

MOTOR CONTROL

SUBROUTINE
### 9.3 SECONDS SOFTWARE DELAY SUBROUTINE

- 0600 A9 LDA #1F
- 0602 A2 LDX #AE
- 0604 A0 LDY #ER
- 0606 CA DEX
- 0607 D0 BNE 0605
- 0609 68 DEY
- 060B D0 BNE 0605
- 060C 38 SEC
- 060D E9 SBC #01
- 060F D0 BNE 0605
- 0611 63 RTS

### LOOK-UP TABLE FOR CALIBRATION DATA

| CMD: 4120 | FF FF 00 00 00 FF FF FF FF FF FF FF FF FF FF FF FF FF FF |
FIGURE 6.7
6.3.4 Motion Characteristics of the Crankshafts

The MPU's X-register is used for all the countings to indicate the various positions of the cranks. In this presentation the straight line is given 32 x-positions while the circle is given 256 (see Table 6.2). For the former, \( x = 0 \) corresponds to the park position while \( x = 1F \) corresponds to the start position.

Figure 6.8 shows traces of the positions of the cranks during the Park-Start and Stop-Park motions. The limits of the motion of Crank A are indicated by arc ab in the forward motion and arc ba in the return motion from the stop position back to the park position. Crank B on the other hand makes a clockwise motion cd and stops at \( x = OA \), reverses and makes a counterclockwise motion indicated by arc de till \( x = 1F \). During the return motion, it makes a clockwise motion shown by arc ef, and later a counterclockwise motion to the park position. This is indicated by arc fg.

In the tracing of the 250 mm diameter circle, Crank A (see Figure 6.9) starts from a start position when \( x = 0 \) and makes a clockwise motion, shown by arc ab, to b. There it stops (i.e. at \( x = 20 \)), reverses and makes a counter clockwise motion (indicated by arc cd) to d. At d (\( x = 9D \)), it again stops, reverses and takes a clockwise direction (as shown by arc ef to the start position. Crank B's motion is similar and is indicated by the path ghijk\( L \), with reversal in directions at \( x = 5F \) and at \( x = E2 \).

A summary of the two crank motions and their corresponding motor velocity data are given in Table 6.3 for both paths. From
<table>
<thead>
<tr>
<th>MD</th>
<th>7000</th>
<th>6A 08 5F BD</th>
<th>MD</th>
<th>7200</th>
<th>F6 02 94 6D</th>
</tr>
</thead>
<tbody>
<tr>
<td>7004</td>
<td>22</td>
<td>8B FD 6B</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7008</td>
<td>E0 58 D3 4F</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>700C</td>
<td>CD 4D CD 4F</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7010</td>
<td>D1 53 D5 57</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7014</td>
<td>D5 5A DB 5A</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7018</td>
<td>D7 53 CD 4F</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>701C</td>
<td>B9 2B 97 60</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MD</td>
<td>7100</td>
<td>16 16 0F 6E</td>
<td>MD</td>
<td>7300</td>
<td>00 00 00 00</td>
</tr>
<tr>
<td>7104</td>
<td>0E 00 3C 6C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7108</td>
<td>0E 08 0A 6A</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>710C</td>
<td>09 05 03 03</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7110</td>
<td>07 07 05 05</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7114</td>
<td>05 05 04 04</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7118</td>
<td>03 01 02 02</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>711C</td>
<td>01 01 00 00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**TABLE 6.2: Data Tables for Crankshaft Positions**
Table 6.2: it was possible to obtain a sequential set of data corresponding to the various critical positions of the cranks. These were used to develop the motor's positioning subroutines of the main programme (see pages 154-161).

Table 6.4 and Figure 6.10 are reproduced from (19) to enhance quick reference to the MDU's memory map.

6.3.5 Checking for Real-Time Operations

For the P-S motion of Point C of the RANDOMM mechanism it is unimportant what time it takes to complete the motion.

Besides it is unimportant if the path is not truly straight.

In its motion around the maximum circle, N cannot be totally arbitrary. It must have a limit. Assuming a constant velocity around the circle and that it takes the microcomputer a time, T_e, to execute all the op-codes in a cycle of operation, the relationship between T_e and N is given by: \( T_e \leq \frac{1}{N+1} \) seconds.

For \( N = 255 \), \( T_e \) must be less than or equal to 3910 \( \mu s \). If less, it should equal \( \frac{f}{(N+1)} \), where \( f \) is an integer.

\( T_e \), itself, depends on such factors as the MPU wordlength, the time it takes to execute all the op-codes and do all the computations, the mode in which the MPU is driven and, of course, on the MPU's machine cycle. The machine cycle time is fixed for each MPU (1 \( \mu s \) for the AIM 65; 500 ns for Intel 8080). The wordlength,
### TABLE 6.3: DATA CHART FOR MOTORS VELOCITIES

<table>
<thead>
<tr>
<th>X-Count</th>
<th>Action</th>
<th>CRANK A</th>
<th>CRANK B</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Hi-byte</td>
<td>Lo-byte</td>
<td>Hi-byte</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$4100</td>
<td>$4000</td>
<td>$4300</td>
</tr>
<tr>
<td>x = 00</td>
<td>Start both motors in clockwise (cw) directions for P-S motion</td>
<td>04</td>
<td>00</td>
<td>04</td>
</tr>
<tr>
<td></td>
<td>Input first set of data</td>
<td>10</td>
<td>BA</td>
<td>00</td>
</tr>
<tr>
<td>x = 0A</td>
<td>Stop both motors</td>
<td>08</td>
<td>00</td>
<td>08</td>
</tr>
<tr>
<td></td>
<td>Reverse the direction of B. Continue with A in the same direction</td>
<td>04</td>
<td>00</td>
<td>0C</td>
</tr>
<tr>
<td>x = 1F</td>
<td>Stop both motors</td>
<td>08</td>
<td>00</td>
<td>08</td>
</tr>
<tr>
<td></td>
<td>For motion along circle: start both motors with initial speeds. A in</td>
<td>04</td>
<td>00</td>
<td>0C</td>
</tr>
<tr>
<td></td>
<td>counterclockwise (ccw) and B in cw directions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>x = 00</td>
<td>Input motors initial position values</td>
<td>02</td>
<td>58</td>
<td>02</td>
</tr>
</tbody>
</table>

/continued...
<table>
<thead>
<tr>
<th>x  = 20</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Stop both motors</td>
<td>08</td>
<td>00</td>
<td>08</td>
<td>00</td>
</tr>
<tr>
<td>Reverse direction of A.</td>
<td>0C</td>
<td>00</td>
<td>0C</td>
<td>00</td>
</tr>
<tr>
<td>Maintain direction of B.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>x  = 5F</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Stop both motors</td>
<td>08</td>
<td>00</td>
<td>08</td>
<td>00</td>
</tr>
<tr>
<td>Maintain direction of A.</td>
<td>0C</td>
<td>00</td>
<td>04</td>
<td>00</td>
</tr>
<tr>
<td>Reverse direction of B.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>x  = 9D</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Stop both motors.</td>
<td>08</td>
<td>00</td>
<td>08</td>
<td>00</td>
</tr>
<tr>
<td>Reverse direction of A.</td>
<td>04</td>
<td>00</td>
<td>04</td>
<td>00</td>
</tr>
<tr>
<td>Maintain direction of B.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>x  = E2</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Stop both motors</td>
<td>08</td>
<td>00</td>
<td>08</td>
<td>00</td>
</tr>
<tr>
<td>Maintain the direction of A.</td>
<td>04</td>
<td>00</td>
<td>0C</td>
<td>00</td>
</tr>
<tr>
<td>Reverse that of B.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>x  = FF</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Stop both motors</td>
<td>08</td>
<td>00</td>
<td>08</td>
<td>00</td>
</tr>
<tr>
<td>Start both motors. A ccw; B cw. Give average initial speeds</td>
<td>0C</td>
<td>00</td>
<td>04</td>
<td>00</td>
</tr>
<tr>
<td>Input first set of position values</td>
<td>00</td>
<td>00</td>
<td>02</td>
<td>F0</td>
</tr>
<tr>
<td>Data not part of table</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>x  = 0A</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Stop both motors</td>
<td>08</td>
<td>00</td>
<td>08</td>
<td>00</td>
</tr>
<tr>
<td>Reverse direction of B.</td>
<td>04</td>
<td>00</td>
<td>0C</td>
<td>00</td>
</tr>
<tr>
<td>Maintain that of A</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>x  = 0</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Stop both motors</td>
<td>08</td>
<td>00</td>
<td>08</td>
<td>00</td>
</tr>
</tbody>
</table>
### TABLE 6.3: (Reproduced from (19))

<table>
<thead>
<tr>
<th>Location</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>A000</td>
<td>Port B Output Data Register (ORB)</td>
</tr>
<tr>
<td>A001</td>
<td>Port A Output Data Register (ORA) Controls handshake</td>
</tr>
<tr>
<td>A002</td>
<td>Port B Data Direction Register (DDRB) 0 = Input</td>
</tr>
<tr>
<td>A003</td>
<td>Port A Data Direction Register (DDRA) 1 = Output</td>
</tr>
<tr>
<td>A004</td>
<td>Timer R/W = L R/W = H</td>
</tr>
<tr>
<td>A005</td>
<td>T1 Write T1L-L Read T1C-L Clear T1 Interrupt Flag</td>
</tr>
<tr>
<td>A006</td>
<td>T1 Write T1L-H &amp; T1C-H T1L-L = T1C-L Read T1C-H Clear T1 Interrupt Flag</td>
</tr>
<tr>
<td>A007</td>
<td>T1 Write T1L-L Read T1L-L Read T1L-H</td>
</tr>
<tr>
<td>A008</td>
<td>T2 Write T2L-L Read T2C-L Clear T2 Interrupt Flag</td>
</tr>
<tr>
<td>A009</td>
<td>T2 Write T2C-H T2L-L = T2C-L Read T2C-H Clear T2 Interrupt Flag</td>
</tr>
<tr>
<td>A01A</td>
<td>Shift Register (SR)</td>
</tr>
<tr>
<td>A01B</td>
<td>Auxiliary Control Register (ACR)</td>
</tr>
<tr>
<td>A01C</td>
<td>Peripheral Control Register (PCR)</td>
</tr>
<tr>
<td>A01D</td>
<td>Interrupt Flag Register (IFR)</td>
</tr>
<tr>
<td>A01F</td>
<td>Interrupt Enable Register (IER)</td>
</tr>
<tr>
<td>A01F</td>
<td>Port A Output Data Register (ORA) No effect on handshake</td>
</tr>
</tbody>
</table>

### FIGURE 6.10: (Reproduced from (19))
in our case, is of the order of 16-bits maximum, i.e. a two-byte word length on the AIM. The data table strategy has already saved an enormous length of computation time.

If \( N > 255 \) page boundaries are crossed, and the \( X-/Y- \) registers will have to be re-loaded. This would yield two values of \( T_e \). In order to avoid this, some delay periods will have to be included in the first part of the programme, to make the two \( T_e \) values equal. \( T_e \) will vary if the MPU is driven in the interrupt mode, rather than in the programmed I/O mode. The variation, as in the case of \( N > 255 \), can be handled by the inclusion of delay periods.

\( T_e \) is also affected by the speeds of major components of the peripherals. For example, the reading of a two-byte data from the encoders for storage or/and for comparison with the command data in the data table should be completed before the counter's positions change. For a motor running at 3650 rpm, the encoder will output \( \frac{3650 \times 256}{60} \) counts/sec. This means that 1 encoder count lasts for 64 \( \mu \)s or for 87 \( \mu \)s if motor speed falls to 2700 rpm. There is also the time needed to convert the motor shaft's analogue output into a serial digital output and from that to a parallel word output. But these take negligibly small times.
6.4 The Programme

A flowchart giving an outline of the programme is given in Figure 6.11. The first stage is developed for the straight line motion while the second is for the motion along the circle. The return motion to the park position is the reverse of the straight line motion and is therefore not shown in the diagram. It was also thought inexpedient to draw a flow chart for "Sub-routine 0300" (the execution section of the programme) as the explanation in the programme text is just as straightforward and clear.

The programme is presented on pp.153-60 and incorporates the data tables. A detailed description of the various stages and procedures is also given. However, some major decisions taken need further clarification.

1. The closed loop nature of the mechanism demands extra care in the operation of the system. On no account should the cranks be allowed to make full turns. The first three lines of the programme ensures this safety. The motors are to be switched on only after the programme has started to run.
FIGURE 6.11: The Flow chart

Continued

SRT 2
SRT 1
SRT 4
SRT 3
SRT 1
SRT 4
SRT 3
SRT 1

X = X + 1

X = 31?

X = X + 1

X = 10?

Send Lo-byte data to $4000

X = 0

SRT 2
SRT 1
SRT 1
SRT 2

Initialises/orders motors, speeds and directions

Keeps the zero data on the motors over a long time during which the motors are then switched on.

Executes movement of crankshafts by reading encoders, comparing values with data tables and outputting errors in the DAC's

Sends zero data to both motors.
This section repeats the first part of the flow chart but in the reverse order.
Start programme by sending stop data to both motors A and B

Give 28.5 seconds delay during which the motors are switched on. Don’t run motors first.

Send Lo-byte control data to memory locations 4000 and 4002.

Leave space for a “JMP 003F” in case only the circle is to be traced.

Set X counter to zero.

Stop both motors and zero encoders.

Set both motors in clockwise (cw) direction.

Execute movement programme.

Re-execute nine times and branch out of loop.

Stop both motors briefly.

Re-order them A (cw), B counterclockwise (ccw).

Execute movement programme.

Re-execute nineteen more times.

Stop both motors.

And delay the stoppage for 3.3 secs.

Leave space for “JMP 0089” in case only the straight line motion alone is to be traced.

Start tracing of circle. Set no. of times circle is to be traced.

Zero X-count for no. of equal units on the circle.

Stop both motors. Zero encoders.

Give A ccw motion and B a cw motion.

Execute movement programme for circle.

Re-execute thirty-one more times.

Stop both motors.

Run both motors in cw direction at 1800 rpm.

Execute movement programme.

Re-execute 62 more times.

Stop both motors.

Put A in cw and B in ccw directions.

Execute movement programme.

Re-execute 62 more times.
Stop both motors.

Re-order motors - A c/w B c/w
Execute the control programs.

Stop both motors.

Put A in c/w and B in c/w at 1800 rpm.

Stop both motors briefly.

Repeat the tracing of the circle four more times.

Stop both motors for 3.3 secs to start the return to the park position.

Set X-count to 31.

Stop motors and zero encoders.

Put motor A in c/w and B in c/w directions.

Execute the control programs for straight line.

Make Ports A and B into output ports.

Disable Hi-byte control line at Port B.

Read Hi-byte data for Motor A and store at Port A.

Latch data to DAC A.

Disable the Hi-byte control line again.

Disable the Lo-byte control line at Port B.

Read Lo-byte for Motor A and store at Port A.

Latch Lo-byte to DAC A.

Disable Lo-byte control line of Motor A at Port B.
022F 8D STA #000  
0232 A9 LDA #78  
0234 8D STA #000  
0237 AD LDA #003  
0239 8D STA #001  
023A 89 LDA #5A  
023F 8D STA #000  
0242 A9 LDA #78  
0244 8D STA #000  
0247 A9 LDA #78  
0249 8D STA #000  
024C AD LDA #002  
024F 8D STA #001  
0252 A9 LDA #58  
0254 8D STA #000  
0257 A9 LDA #78  
0259 8D STA #000  
025C 8D RTS  

Disabling Hi-byte control line of Motor B at Port B.
Read Hi-byte data for Motor B and store at Port A.
Latch data into DAC B.
Disable the appropriate control lines.
Disable Lo-byte control lines at Port B.
Disable Hi-byte.
Read Lo-byte to DAC B.
Disable its control lines at Port B.

Return

<K>**=0270
/05
0270 A9 LDA #08  
0272 8D STA #001  
0275 A9 LDA #08  
0277 8D STA #001  
027A 4C JMP 0290  

Motors' Hi-byte control data.

<K>**=0280
/05
0280 A9 LDA #04  
0282 8D STA #001  
0285 A9 LDA #04  
0287 8D STA #001  
028A 4C JMP 0290  

<K>**=0290
/05
0290 A9 LDA #0C  
0292 8D STA #001  
0295 A9 LDA #0C  
0297 8D STA #001  
029A 4C JMP 0290  

<K>**=0290
/05
0290 A9 LDA #0C  
0292 8D STA #001  
0295 A9 LDA #0C  
0297 8D STA #001  
029A 4C JMP 0290  

<K>**=0290
/05
0290 A9 LDA #0C  
0292 8D STA #001  
0295 A9 LDA #0C  
0297 8D STA #001  
029A 4C JMP 0290  

<K>**=0290
/05
0290 A9 LDA #0C  
0292 8D STA #001  
0295 A9 LDA #0C  
0297 8D STA #001  
029A 4C JMP 0290  

<K>**=0290
/05
0290 A9 LDA #0C  
0292 8D STA #001  
0295 A9 LDA #0C  
0297 8D STA #001  
029A 4C JMP 0290  

<K>**=0290
/05
0290 A9 LDA #0C  
0292 8D STA #001  
0295 A9 LDA #0C  
0297 8D STA #001  
029A 4C JMP 0290  

(*)=0300
CONTROL PROGRAMME FOR CIRCLE

SET no. of times programme is to be executed.

Configure Port B into an output port.
And Port A into an input port.

Read encoder A's Hi- and Lo-data bytes.
Load accumulator with Lo data from DATA TABLE
Subtract Lo-data read from Encoder A.
Store result at $6400, X. Read Hi-data from Table. Subtract Hi-data of the encoder and
store result at $6600, X.

Make Port A into an output port.

Send both data to DAC A.
Make Port A into an input port.

Read encoder B's Hi- and Lo-data bytes.

Carry out similar process as for axis A above.

Make Port A into an output port and latch
the data to DAC B.

Repeat procedure six more times.

RETURN.
I 6400
35
0400 A9 LDA #78 Disable Enc. A Hi-byte control lines at
0402 BD STA A600 at Port B.
0405 A9 LDA #71 Enable the lines to transfer data to
0407 BD STA A600 Port A
040A A9 LDA #61 Read the data. Mask off the 3 MSB.
040D 29 AND #1F
040F BD STA 5600,X Store data at 5600, X.
0412 A9 LDA #78 Disable Hi-byte control lines again.
0414 BD STA A6000
0417 A9 LDA #79 Disable Lo-byte control line of Enc. A.
0419 BD STA A6000
041C A9 LDA #70 Enable the lines to transfer data
041E BD STA A600 instantly.
0421 A9 LDA #61 Read off data from Port A and store at loc.
0424 BD STA 5400,X Disable Lo-data control lines.
0427 A9 LDA #79 and return.
0429 BD STA A600
042C 60 RTS

0440 A9 LDA #79 Disable Hi-byte control lines to DAC A.
0442 BD STA A500
0445 BD LDA 5600,X Load Hi-byte from $5600, X and send to
0448 BD STA A601 Port A.
044B A9 LDA #65 Enable the Hi-byte control lines to latch
044D BD STA A600 data to DAC A.
0450 A9 LDA #75 Disable the lines.
0452 BD STA A600
0455 A9 LDA #78 Disable Lo-byte control lines to DAC A.
0457 BD STA A600
045A BD LDA 5400,X Load Lo-byte from $5400, X and send data to Port A.
045D BD STA A601 Enable the data to latch it to DAC A.
045E A9 LDA #65 Disable the control lines.
045F A9 LDA #68 Give DAC A 10 μs settling time to convert data to
0464 BD STA A600 voltage
0467 BD STA A600 and return
046A 20 JSR 0550
046D 60 RTS
<table>
<thead>
<tr>
<th>Address</th>
<th>Instruction</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0480 A9 LDA #78</td>
<td>Disable Enc. B Hi-byte control lines at Port B.</td>
<td></td>
</tr>
<tr>
<td>0482 ED STA A000</td>
<td>Enable the lines to transfer data from Enc. B to Port A.</td>
<td></td>
</tr>
<tr>
<td>0485 A9 LDA #73</td>
<td>Load data from Port A and mask off the 3 MSB.</td>
<td></td>
</tr>
<tr>
<td>0487 ED STA A000</td>
<td>Store data at $6A00,X.</td>
<td></td>
</tr>
<tr>
<td>048A A9 LDA A001</td>
<td>Disable Hi-byte control lines.</td>
<td></td>
</tr>
<tr>
<td>048C A9 LDA #78</td>
<td>Disable Enc. B Lo-byte control lines.</td>
<td></td>
</tr>
<tr>
<td>0492 A9 LDA #78</td>
<td>Enable for data transfer to Port A.</td>
<td></td>
</tr>
<tr>
<td>0494 ED STA A000</td>
<td>Read Port A and store data at mem. loc. $8000,X.</td>
<td></td>
</tr>
<tr>
<td>0496 A9 LDA #78</td>
<td>Disable control lines.</td>
<td></td>
</tr>
<tr>
<td>0498 A9 LDA #78</td>
<td>Re-disable and Return.</td>
<td></td>
</tr>
<tr>
<td>049A ED STA A000</td>
<td>DisabZe aontroZ Zines.</td>
<td></td>
</tr>
<tr>
<td>049C A9 LDA #72</td>
<td>Store data at $6A00,X.</td>
<td></td>
</tr>
<tr>
<td>049E ED STA A000</td>
<td>DisabZe Hi-byte aontroZ Zines.</td>
<td></td>
</tr>
<tr>
<td>04A1 A9 LDA #70</td>
<td>Load Hi-byte and send to Port A.</td>
<td></td>
</tr>
<tr>
<td>04A3 A9 LDA #78</td>
<td>Enable its control lines to latch data to DACB.</td>
<td></td>
</tr>
<tr>
<td>04A5 A9 LDA #78</td>
<td>DisabZe the lines.</td>
<td></td>
</tr>
<tr>
<td>04A7 A9 LDA #78</td>
<td>DisabZe Lo-byte control lines.</td>
<td></td>
</tr>
<tr>
<td>04A9 A9 LDA #78</td>
<td>Load Lo-byte from mem. loc. and send to Port A.</td>
<td></td>
</tr>
<tr>
<td>04AC A9 LDA #78</td>
<td>Enable Lo-byte control lines to latch the data to DAC B.</td>
<td></td>
</tr>
<tr>
<td>04B0 A9 LDA #78</td>
<td>Disable the control lines.</td>
<td></td>
</tr>
<tr>
<td>04B2 ED STA A000</td>
<td>Give DAC B 16 µs settling time.</td>
<td></td>
</tr>
<tr>
<td>04B5 A9 LDA #78</td>
<td>and Return.</td>
<td></td>
</tr>
</tbody>
</table>
STOPPAGE OF MOTORS AND ZEROING OF ENCODERS

16 µs delay. DAC's settling time is 15 µs.
(K)\* = 0600
112
0600 A2 LDX #A5
0602 A0 LDY #EA
0604 CA DEX
0605 D0 BNE 0604
0607 88 DEY
0608 D0 BNE 0604
060A 38 SEC
060B E9 SBC #01
060D D0 BNE 0608
060F 60 RTS

LONG DELAY
Timing byte is stored in accumulator...

300 ms delay.

Return

(K)\* = 0620
99
0620 A9 LDA #FF
0622 6D STA 0002
0625 A9 LDA #00
0627 3D STA 0003
062A 20 JSR 0400
062D 38 SEC
0635 BD LDA 5000.X
0631 FD SBC 7000.X
0634 3D STA 5000.X
0637 BD LDA 5100.X
0639 FD SBC 7100.X
063D 3D STA 5100.X
0640 A9 LDA #FF
0642 6D STA 0003
0645 10 JSR 0440
0648 A9 LDA #00
064A 6D STA 0003
064D 20 JSR 0480
0650 38 SEC
0655 BD LDA 5200.X
0651 FD SBC 7200.X
0654 3D STA 5200.X
0657 BD LDA 5300.X
0659 FD SBC 7300.X
065D 3D STA 5300.X
0663 A9 LDA #FF
0665 3D STA 0003
0668 20 JSR 04D0
066B 60 RTS

RETURN

$7000-7AFF

CONTROL PROGRAMME FOR STRAIGHT LINE

(Instructions are same as for circle)

Return

DATA TABLES
6.5 *Tests*

The section of the programme that deals with motion along the circle was tested, with the mechanism uncoupled (in order to avoid risks). In its first run, which did not include the stop and reverse and initialise speed subroutines (SRT 1 and 3 of the flowchart), the response of the motors was erratic, although they seemed to keep to the expected motion pattern. It was also noticed that the angles of oscillation of the crankshafts were much less than the stipulated 71.85°.

A decision was then taken to give each crank an initial velocity at the start of each of the 255 units of the complete motion, hence SRT 3. This increased the angles of oscillation by a large margin. Both cranks were given the same initial speeds simultaneously and it was hoped that subroutine four, SRT 4, would adjust the speeds accordingly. In the first test, the starting position of each of the five cycles of the crankshaft motion was not constant. Subroutine 1 (SRT 1) was intended to correct this. One area of discrepancy, as anticipated in Section 6.3.5, remained unresolved. The execution time, $T_e$, of the subroutine labelled "SRT 4" is 797 microseconds. The time it takes the encoder to undergo 1 LSB change with the motors running at about 1800 rpm is 130 microseconds. To make the two values equal, the motors would have to be run at 294 rpm - a speed that is extremely low, if not meaningless. Alternatively two MPU's should be used, one for each motor.
In order that the angles of oscillation be fixed, all operations must start from a fixed or park position. This position would be located by a pair of microswitches, or, preferably, opto-detectors. Both would act as switches to an external, hard-wired circuit that switches off or stops the motors once that position is reached.

This requirement now calls for a modification of the Data Logger Programme. Instructions and guidelines to this modification are given in Appendix G. It also means that the encoders must be zeroed at the start and end of the park-start motion and at the start and end of the circular path.

Further debugging of the main programme was halted when one of the motors failed and was sent out for repair. A report from the manufacturer where it was sent stated that it became overheated due to excess current. The MPU also had to be sent for repair as it failed to print and display correct characters.

It must be mentioned here, that there is the alternative in the marking of the crankshaft's reversal points. The above programme uses X-counts to locate these positions. It is possible to do the same using encoder counts.

Finally, it would be observed that the initial angular velocities given to each motor at the start of each of the 255 units of crank motion is the same in magnitude. In tracing the circle, the two motors must not be run at the same speed. It had been assumed that the necessary differences in the speeds would be provided for when corresponding error signals are sent out to the
DAC's for subsequent adjustments to the initial velocities. A method of ascertaining these speeds and their directions is presented in Appendix H.
CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

The limitations of the AIM 6502 MPU both in its I/O handling and editing made programming more tedious. The unavailability of the motor/tacho control component in one of the control circuits led to an incomplete test. But judging by the results visually obtained for the left hand crank, there are indications that the control programme will work when both axes of drive are simultaneously worked and the MPU changed to one with a machine cycle less than one microsecond and having separate 8-bit control ports.

On the adaptation of the RANDOMM mechanism to such other needs as robotic welding and cutting, the device will join a few others such as the Orbit of ESAB (23) – a Swedish company and the Daros F10 of Dainichi – Sykes (24) – a Japanese manufacturer, as a 2- or 3-axis robotic manipulator. It will be a cheaper and more rigid device than the Daros which has less rigidity and vibrates markedly when in operation. Its cost of £38,000 is prohibitive. A RANDOMM equivalent is expected to cost less than £6000.

The mechanism's first application is likely to be in its 2-dof form as a manipulator for an air plasma torch for use in flat welding. A small-scale Loughborough firm has already shown interests.
7.1 Areas for Further Work

The next immediate stages of the project should involve:

1. The perfection of the main programme and the development of similar programmes for other paths.

2. The application of the 2 dof RANDOMM to flat welding and air plasma cutting.

3. An improvement on the method of sensing the position of the output point of the mechanism, and in the long run

4. Application of the work to other machine types.

7.2 Recommendations

The author wishes to suggest that work on further development of the project be taken up more seriously through the provision of sufficient funds. Such funds would go into the provision of MPU with a full development system. The processor should have a machine cycle of 0.5 microseconds, and there should be a separate 8-bit control port and two 8-bit I/O ports.
BIBLIOGRAPHY


22. Rockwell, AIM 65 Microcomputer - User's Guide
   - Programming Manual
   - Basic Language Reference Manual


24. Dainichi-Sykes, Japan.


26. Carlisle, B. H.

LIST
1 PRINT "PARAM15"
2 PRINT "MODE 1"
3 REM INITIAL CONDITIONS
5 READ U0, U0, U1, U1
10 DATA 16, 55, 11, 38.5
15 READ U2, U2, U3, U3
20 DATA 17, 43, 26, 45
25 READ U4, U4
30 DATA 32.68, 50.2
35 INPUT L, K
40 READ L1, L2, L3, L4
50 DATA 45.1, 21.52, 44, 12.5
55 READ X5, Y5, X6, Y6
70 DATA 45.1, 0, 22.55, 44
80 READ X7, Y7, X8, Y8
90 DATA 22.55, 20, 33.03, 44
96 WINDOW -30, 70, -30, 70
100 VIEWPORT 0, 100, 0, 100
102 SET DEGREES
105 AXIS 10, 10, 0, 0
110 GOSUB 1045
112 GO TO 1135
115 INPUT M
120 PRINT "X", "Y", "A2", "A5"
130 PRINT "CM", "CM", "DEG", "DEG"
135 PRINT "RESULTS FOR STR LINE"
150 FOR I = 0 TO M
160 X = X7 + I * (X8 - X7) / M
170 Y = Y7 + I * (Y8 - Y7) / M
180 GOSUB 700
190 GOSUB 500
200 NEXT I
205 END
240 X = INT(X * 10000 + 0.5) / 10000
245 Y=INT(Y$10000+0.5)/10000
250 PRINT X,Y,A2,A5
260 NEXT I
270 PRINT
280 PRINT
290 PRINT "RESULTS FOR CIRCULAR PATH"
300 PRINT "I","X","Y","A2","A5"
310 PRINT "   "
320 PRINT "DEG","CM","CM","DEG","DEG"
330 GOSUB 1045
340 FOR I=0 TO N
350 X=L4*COS(360*I/M)+X6
360 Y=L4*SIN(360*I/M)+Y6
370 GOSUB 700
380 GOSUB 500
390 NEXT I
400 MOVE 22.55,44
410 PRINT "++"
420 GO TO 950
430 A2=INT(A2$10000+0.5)/10000
440 A5=INT(A5$10000+0.5)/10000
450 PRINT 360*I/M,X,Y,A2,A5
460 NEXT I
470 END
480 MOVE 0,0
490 DRAW X2,Y2
500 DRAW X,Y
510 DRAW X4,Y4
525 DRAW 45.1,0
540 RETURN
550 S1=L2+X2+Y2-L3
560 S2=2*L2*SQR(X2+Y2)
570 S3=(L1-X)*2+Y2+L2-L3
580 S4=2*L2*SQR((L1-X)*2+Y2)
590 A2=ATN(Y/X)+AC8(S1/S2)
750 A5=180-ATN(Y/(L1-X))-ACS(S3/S4)
760 X2=L2*COS(A2)
770 Y2=L2*SIN(A2)
780 A3=ACS((X-X2)/L3)
790 X4=X5+L2*COS(A5)
800 Y4=L2*SIN(A5)
810 A4=180-ACS((Y-Y4)/L3)
820 X0=0.5*L2*COS(A2)
830 Y0=0.5*L2*SIN(A2)
840 X1=0.5*L3*COS(A3)+X2
850 Y1=0.5*L3*SIN(A3)+Y2
860 X3=0.5*L3*COS(A4)+X
870 Y3=0.5*L3*SIN(A4)+Y
880 X9=0.5*COS(A5)+X5
890 Y9=0.5*L2*SIN(A5)+Y5
900 RETURN
950 REM LABELS
960 FOR I=0 TO 72 STEP 10
970 MOVE 0,I
980 PRINT "HHH";I;
990 MOVE I,0
1000 PRINT "J";I;
1010 NEXT I
1020 MOVE 20,-30
1025 PRINT "POSITION PLOT FOR RANDOM MECHANISM"
1040 END
1045 MOVE 35.05,44
1050 FOR I=0 TO 72
1055 X=L4*COS(360*I/72)+X6
1060 Y=L4*SIN(360*I/72)+Y6
1065 DRAW X,Y
1070 NEXT I
1075 RETURN
1105 REM NO OF UNITS:STR LINES&I/4CIRCLE
1130 MOVE U1,U1
DRAW U2, U2
DRAW U3, U3
DRAW U4, U4
REM
REM
L9=SQR((U4-U0)\^2+(U4-U0)\^2)
T9=ACOS((U4-U0)/L9)
FOR I=0 TO K
X=U0+L9*COS(T9+90*I/K)
Y=U0-L9*SIN(T9+90*I/K)
DRAW X, Y
NEXT I
FOR I=0 TO L
X=U1+I*(U2-U1)/L
Y=U1+I*(U2-U1)/L
GOSUB 700
GOSUB 500
NEXT I
FOR I=1 TO L
X=U2+I*(U3-U2)/L
Y=U2+I*(U3-U2)/L
GOSUB 700
GOSUB 500
NEXT I
FOR I=1 TO L
X=U3+I*(U4-U3)/L
Y=U3+I*(U4-U3)/L
GOSUB 700
GOSUB 500
NEXT I
FOR I=1 TO L
X=U4+I*(U1-U4)/L
Y=U4+I*(U1-U4)/L
GOSUB 700
GO TO 1318
FOR I=1 TO L
X=U4+I*(U1-U4)/L
Y=U4+I*(U1-U4)/L
GOSUB 700
1300 GOSUB 700
1305 GOSUB 500
1310 NEXT I
1315 GO TO 960
1318 FOR I=1 TO L
1320 X=V0+L9*COS(T9+90*I/L)
1325 Y=V0-L9*SIN(T9+90*I/L)
1330 GOSUB 700
1335 GOSUB 500
1340 NEXT I
1345 GO TO 960
END OF SEGMENT, LENGTH 10, NAME RANDTORQ

APPENDIX B1

0016 SUBROUTINE BRGWRITE
0017 DIMENSION X2(2), Y2(2), X(9), Y(9), B(27), B(27), LNH(27), LN(27), AL(27),
0018 1C(27), 2D(27), 3D(27), 4D(27), 5D(27), 6D(27), 7D(27), 8D(27), 9D(27), 10D(27),
0019 DIMENSION R(9), X(9), Y(9)
0020 DIMENSION Z(9), A(9)
0021 REAL M(3), L(3), A(3)
0022 REAL H(2), D(2)
0023 COMMON H, P, DEG, RAD
0024 COMMON /B1/ SN, SLLINN, NLS, NLS, X1, V1, V2, V3
0025 COMMON /B2/ L, AV
0026 COMMON /B3/ X, Y, Z, R
0027 COMMON /B4/ L, DH
0028 COMMON /B5/ X1, V1, Z1, R1
0029 COMMON /B6/ X2, Y2, Z2, R2
0030 COMMON /B7/ M, IF
0031 V4V4
0032 661 CALL DIFFS
0033 CALL RPA(X, Y, Z, R, L, V, P, A)
0034 NSTOREN
0035 C CARDS UNTIL COMMENT 'STANDARD ROUTINE MUST CHANGE WITH RPA_SUB'
0036 C CHANGE COMMON /B10/ WHEN CHANGING RPA_SUB
0037 C COMPARE /B10/ XA, YA, ZA, XA, YA, XA, YC, XA, YD, XA, YC
0038 CALL RPA(X, Y, Z, R, L, V, P, A)
C SOLN WILL GIVE AX,AY,BX,BY,CX,CY,DX,DY,EX,EY,T2,T5

DO 680 I=1,N

680 R0(1:1) = R0(1:1) + 0.002

IF(V.GT.V1+0.001) GO TO 445

WRITE*(2,625) V10

625 FORMAT('0X11 VALUES OF MATRIX BF FOR V=',F9.0,'/I')

DO 672 I=1,N

WRITE*(2,630) (BF(I,J),J=1,N)

630 FORMAT(15F5.3)

672 CONTINUE

C FORMAT 630 NEEDS TO BE CHANGED IF BF IS LARGER THAN 15X15

632 FORMAT('0X11 VALUES OF RHS /I')

WRITE*(2,640) (RHS(I,1),I=1,N)

640 FORMAT(62X,F11.3)

WRITE*(2,655)
0101.  655.  FORMAT(6DX, 1, VALUES OF BEARING LOADS) 724X, 1, VALUES OF TORQUE 1)
0102.  649.  IFAIL=1
0103.  CALL FO4AEF(0F, 27, RH, 27, N, 2, SOLN, 27, AL2CROUT, 27, RESID, 27, IFAIL)
0104.  IF(IFAIL.EQ.0) GO TO 620
0105.  WRITE(2,650) IFAIL
0106.  650.  FORMAT(1 Failure in FO4AEF, IFAIL = '13X, 12)
0107.  620.  RW2=0.
0108.  C 4. RW1 AND RW2 ARE INDEPENDENT ESTIMATES OF TOTAL RATE OF WORKING
0109.  C 4. IN HAFS, TORQ IS NET TORQUE REQUIRED=T2+TS
0110.  RW1=OM*([SOLN(11,1)+R1(2)+SOLN(12,1)+R1(5)]
0111.  DO 664 J=1,NSTORE
0112.  664.  RW2=RW2+OM*3*(MF(J)*X2(J)*X1(J)+V2(J)*V1(J)) + IF(J)*R2(J)*R1(J)
0113.  TORQ=SOLN(971)+SOLN(10,1)
0114.  V=V+DEG
0115.  WRITE (2,660) V+NSOLVE(1)+IP1+IP2+RW1/RW2
0116.  660.  FORMAT(11E10, 3)
0117.  RW2=0
0118.  N=NSTORE
0119.  V=V+RADEG
0120.  IF(V.LE.V3) GO TO 661
0121.  RETURN
0122.  END

END OF SEGMENT: LENGTH = 1040, NAME: BGSWRITE

0123.  SHORT LIST
0124.  SUBROUTINE RPA(X,Y,Z,R,L,V,P,A)

END OF SEGMENT: LENGTH = 705, NAME: RPA
APPENDIX B2

SUBROUTINE RPA(X,Y,Z,R,1,V,D,A)

RANDOM SUB 10

DIMENSION X(9), Y(9), Z(9), R(9), A(9)

REAL L(33)

COMMON/XA,YA,YB,XG,YG,XD,YD,XE,YE/

X(1)=COS(A(1))

Y(1)=SIN(A(1))

X(2)=COS(A(2))

Y(2)=SIN(A(2))

R(1)=V

X(3)=COS(Y-A(3))

Y(3)=SIN(Y-A(3))

X(4)=COS(V-A(4))

Y(4)=SIN(V-A(4))

CA=SQRT((XC-XA)**2+(YC-YA)**2)

XAC=ATAN_2((YC-YA),(XC-XA))

BCA=ACOS((L(5)**2+CA**2+L(2)**2-2*L(5)*CA)/2)

R(3)=XAC+BCA

X(5)=XG+L(3)*COS(R(3))

Y(5)=YG+L(3)*SIN(R(3))

X(6)=XG+L(3)*COS(R(3))

Y(6)=YG+L(3)*SIN(R(3))

R(2)=ATAN_2((XA-XB)/(YA-YB))

X(7)=XG+L(5)*COS(R(2))

Y(7)=YG+L(5)*SIN(R(2))

CE=SQRT((XC-XE)**2+(YC-YE)**2)

XEC=ATAN_2((YC-YE),(XC-XE))

SEC=ACOS((L(9)**2+CE**2-L(11)**2)/(2.*L(9)*CE))

R(6)=SEC

X(11)=XC+L(10)*COS(R(4)+A(6))

Y(11)=YC+L(10)*SIN(R(4)+A(6))

XD=XC+(R(9)+COS(R(4))

YD=YC+(R(9)+SIN(R(4))

R(5)=P+ATAN_2((YN-YE),(YN-XE))

X(12)=XD+L(22)*COS(R(5)+A(7))

Y(12)=YD+L(22)*SIN(R(5)+A(7))

RETURN

End
### Motor Type Comparison

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Torque</th>
<th>Iron core</th>
<th>Surface wound</th>
<th>Printed</th>
<th>Moving coil</th>
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<tbody>
<tr>
<td>Moment of inertia</td>
<td>large</td>
<td>medium</td>
<td>small</td>
<td>small</td>
<td>very small</td>
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<tr>
<td>Electrical time constant</td>
<td>long</td>
<td>average</td>
<td>short</td>
<td>very short</td>
<td>very short</td>
</tr>
<tr>
<td>Internal damping losses</td>
<td>medium</td>
<td>medium</td>
<td>small</td>
<td>large</td>
<td>small</td>
</tr>
<tr>
<td>High speed performance</td>
<td>poor</td>
<td>good</td>
<td>very good</td>
<td>poor</td>
<td>average</td>
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<tr>
<td>Low speed performance</td>
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<td>good</td>
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<tr>
<td>Armature thermal time constant</td>
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<td>long</td>
<td>average</td>
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<td>very short</td>
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<td>Torque/inertia ratio</td>
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<td>medium</td>
<td>high</td>
<td>high</td>
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<td>Relative cost</td>
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<td>high</td>
<td>medium</td>
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<td>coil</td>
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<td>radial</td>
<td>axial</td>
<td>radial</td>
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<tr>
<td>Commutator radius</td>
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<td>medium</td>
<td>medium</td>
<td>large</td>
<td>medium</td>
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<td>Magnets</td>
<td>Alnico</td>
<td>Alnico/ceramic</td>
<td>Alnico/ceramic</td>
<td>ferrite/Alnico</td>
<td>Alnico</td>
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APPENDIX E
CONTROL BOX WIRING CONNECTIONS

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<tr>
<th>Socket J1</th>
<th>Connections to AIM I/O ports</th>
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<tbody>
<tr>
<td>1</td>
<td>PA₀ White Data</td>
</tr>
<tr>
<td>2</td>
<td>Grey</td>
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<td>3</td>
<td>Purple</td>
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</tr>
<tr>
<td>8</td>
<td>PA₇ Red</td>
</tr>
<tr>
<td>9</td>
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</tr>
<tr>
<td>10</td>
<td>PB₀ Brown Address A₀</td>
</tr>
<tr>
<td>11</td>
<td>PB₁ Black Address A₁</td>
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</tr>
<tr>
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<td>14</td>
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</tr>
<tr>
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</tr>
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<td></td>
</tr>
<tr>
<td>17</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>PB₃ Grey Enable Encoder</td>
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<tr>
<td>19</td>
<td>PB₄ Purple Enable D/A</td>
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<td>PB₅ BlueClr. Enc. 2</td>
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<td>PB₆ GreenClr. Enc. 1</td>
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</tr>
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</tr>
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<td>1</td>
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<tr>
<td>3</td>
<td>-15V</td>
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<td>21</td>
<td>+12V Orange</td>
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<td>23</td>
<td>+5V Red</td>
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<td>25</td>
<td>0V Brown</td>
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### Socket J3

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<td>1 FS2 L</td>
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<tr>
<td>2 FS2 R</td>
<td>Black</td>
</tr>
<tr>
<td>3 FS1 L</td>
<td>Blue</td>
</tr>
<tr>
<td>4 FS1 R</td>
<td>Brown</td>
</tr>
<tr>
<td>5 FS3 L</td>
<td>Orange</td>
</tr>
<tr>
<td>6 FS3 R</td>
<td>Purple</td>
</tr>
<tr>
<td>7 FS4 L</td>
<td>White</td>
</tr>
<tr>
<td>8 FS4 R</td>
<td>Orange</td>
</tr>
<tr>
<td>9 -15V</td>
<td>Yellow</td>
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<tr>
<td>10 OV</td>
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### Tacho and Encoder Sockets

<table>
<thead>
<tr>
<th>LHS</th>
<th>RHS</th>
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<tr>
<td>A</td>
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</tr>
<tr>
<td>B</td>
<td>B</td>
</tr>
<tr>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td>D</td>
<td>D</td>
</tr>
<tr>
<td>E</td>
<td>E</td>
</tr>
<tr>
<td>F</td>
<td>F</td>
</tr>
<tr>
<td>G</td>
<td>G</td>
</tr>
<tr>
<td>H</td>
<td>H</td>
</tr>
</tbody>
</table>

- **A**: Tacho +
- **B**: Tacho -
- **C**: B O/P
- **D**: Zero
- **E**: +5V
- **F**: Screen
- **G**: OV
- **H**: A O/P

### Motor Socket

<table>
<thead>
<tr>
<th>Side</th>
<th>Socket Type</th>
<th>Direction</th>
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<tr>
<td>A</td>
<td>RHS</td>
<td>+ve</td>
</tr>
<tr>
<td>B</td>
<td>RHS</td>
<td>-ve</td>
</tr>
<tr>
<td>C</td>
<td>LHS</td>
<td>+ve</td>
</tr>
<tr>
<td>D</td>
<td>LHS</td>
<td>-ve</td>
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<tr>
<td>Subrack connections</td>
<td>Edge Connector</td>
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<td>---------------------</td>
<td>---------------</td>
<td></td>
</tr>
<tr>
<td><strong>Enc D/A Boards</strong></td>
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<td></td>
</tr>
<tr>
<td>a  b</td>
<td>a</td>
<td></td>
</tr>
<tr>
<td>1     1</td>
<td>1</td>
<td>GND</td>
</tr>
<tr>
<td>2     2</td>
<td>2</td>
<td>+5V</td>
</tr>
<tr>
<td>3     3</td>
<td>3</td>
<td>Zero 1 (LHS)</td>
</tr>
<tr>
<td>4     4</td>
<td>4</td>
<td>Zero 2 (RHS)</td>
</tr>
<tr>
<td>3     5</td>
<td>5</td>
<td>+5V</td>
</tr>
<tr>
<td>6     W/C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7     7 D_0</td>
<td>7</td>
<td>D_0</td>
</tr>
<tr>
<td>8     8 D_1</td>
<td>8</td>
<td>D_1</td>
</tr>
<tr>
<td>9     9 D_2</td>
<td>9</td>
<td>D_2</td>
</tr>
<tr>
<td>10    10 D_3</td>
<td>10</td>
<td>D_3</td>
</tr>
<tr>
<td>11    11 D_4</td>
<td>11</td>
<td>D_4</td>
</tr>
<tr>
<td>12    12 D_5</td>
<td>12</td>
<td>D_5</td>
</tr>
<tr>
<td>13    13 D_6</td>
<td>13</td>
<td>D_6</td>
</tr>
<tr>
<td>14    14 D_7</td>
<td>14</td>
<td>D_7</td>
</tr>
<tr>
<td>16    15 D/A Enable</td>
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<td>17    16 D/A GND 1</td>
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<tr>
<td>18    17 D/A GND 2</td>
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<tr>
<td>17    18 A_0</td>
<td>18</td>
<td>A_0</td>
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<tr>
<td>18    19 A_1</td>
<td>19</td>
<td>A_1</td>
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<tr>
<td>19    20 A_2</td>
<td>20</td>
<td>A_2</td>
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<tr>
<td>20    21 Enc Enable</td>
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<td>21    22 Enc 1A</td>
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<td>22    23 Enc 2A</td>
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<td>Enc 2A</td>
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<td>21    24 D/A Output 1</td>
<td>24</td>
<td>D/A Output 1</td>
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<tr>
<td>22    25 D/A Output 2</td>
<td>25</td>
<td>D/A Output 2</td>
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<tr>
<td>25    26 N/C</td>
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<td>N/C</td>
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<td>25    27 Enc 1B</td>
<td>27</td>
<td>Enc 1B</td>
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<tr>
<td>26    28 Enc 2B</td>
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<td>Enc 2B</td>
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<td>29    29 Clr Enc 1</td>
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<td>Clr Enc 1</td>
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<td>30    30 Clr Enc 2</td>
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<td>Clr Enc 2</td>
</tr>
<tr>
<td>31    31 +15V</td>
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<td>+15V</td>
</tr>
<tr>
<td>32    32 -15V</td>
<td>32</td>
<td>-15V</td>
</tr>
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</table>
**APPENDIX F**

**NO OF STR. LINE UNITS =** | 64
---|---
**NO. OF CIR. UNITS =** | 25
**LEN FS (CM) =** | 12.5
**START ANGLE (RADS) =** | 0

**DIGITAL CONTROL PROG FUNCTIONS**

<table>
<thead>
<tr>
<th>X</th>
<th>Y CM</th>
<th>R2</th>
<th>R4</th>
<th>L</th>
<th>B1</th>
<th>B2</th>
<th>M#</th>
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<tr>
<td>22.55</td>
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<td>2.74643329</td>
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**ZERO-START (STR LINE) PATH**

| 23.115 | 21.115 |
| 2.5637706 | .377021194 |
| 2.267162465 | 4027 | 172 |
| 15 | 0 | 187 | 172 |
| 0FBB | 00AC |

| 23.331 | 21.5 |
| 2.66135476 | .371777929 |
| 2.26692489 | 1946 | 151 |
| 15 | 0 | 106 | 151 |
| 0F6A | 0097 |

| 23.527 | 21.875 |
| 2.64436027 | .366913064 |
| 2.26727254 | 1866 | 131 |
| 15 | 0 | 26 | 131 |
| 0F1A | 0083 |

| 23.722 | 22.25 |
| 2.65252625 | .36243953 |
| 2.267321834 | 2.88286124 | 3768 | 113 |
| 14 | 0 | 204 | 211 |
| 6ECC | 0671 |

| 23.917 | 22.825 |
| 2.606307 | .35932754 |
| 2.26806757 | 2.79162674 | 3712 | 36 |
| 14 | 0 | 128 | 96 |
| 6E88 | 0669 |

<p>| 24.113 | 23 |
| 2.58889152 | .354578812 |
| 2.268854665 | 1.78090562 | 1537 | 31 |
| 14 | 0 | 73 | 81 |
| 6E35 | 0651 |</p>
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<th>Value</th>
<th>Value</th>
<th>Value</th>
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APPENDIX G: MODIFICATION OF THE DATA LOGGER PROGRAMME

151     READ XM, YM
152     DATA 22.55, 31.5
400     X = XM
405     Y = I_0 (YM-YP)/M + YP
Delete 410, 415
256     GO TO 905
905     FOR I = 0 TO M
910     XS = R1 * COS (T1) + XF
915     YS = R1 + SIN (T1) + YF
920     X = XM + I * (XS-XM)/M
925     Y = YM + I * (YS-YM)/M
930     REM ROUND OFF X,Y VALUES
935     X1 = INT (X * 1000 +0.5)/1000
940     Y1 = INT (Y * 1000 +0.5)/1000
945     PRINT X1,Y1
950     GOSUB 450
955     L =
960     0 =
965     PRINT L,0
970     GOSUB 550
975     PRINT B1,B2, C1;C2
980     GOSUB 870
985     GOSUB 800
990     PRINT M$,N$
995     PRINT ": NEXT
1000     GO TO 260
Notes:

1. Lines 200, 210, 955, 960:
   The minimum values of L and O are to be subtracted from A2 and A5 respectively.

2. The choice of XM, YM must be made such that the cranks do not rotate beyond their park positions.

3. M may be different for the two sections. In that case another INPUT instruction has to be included at 19 and 905 changed accordingly.

4. The new path is shown as PMS in Figure 6.8.
APPENDIX H: MOTOR SPEED DATA FORMULA

Referring to Figures A and B:

(X_i, Y_i) is any point along the circular path.

(A_{2i}, A_{5i}) is any pair of equivalent crank angles.

(L_i, O_i) is the corresponding pair of encoder counts (Enc Coun) representing (A_{2i}, A_{5i}).

i = 0, 1, 2, ..., N.

N is the no. of equal units taken along the perimeter of the circular path.
S is the speed of each motor. (in terms of encoder counts/sec).
T is the time needed to trace the circle once.
ω is the maximum allowable speed in rpm of each motor.
H is the DAC signal corresponding to S.

It takes \( \frac{T}{N} \) secs to trace each unit. This means that the crank speed at the beginning of each unit is

\[ S = \frac{(L_{i+1} - L_i)}{(T/N)} \text{ Enc Coun/sec} \]

\[ S_{\text{max}} = \frac{\omega \times 256}{60} \text{ Enc Coun/sec} \]

Thus \( H = 0800h + (0FF - 0800h) \)

For \( T = 5 \) sec, \( N = 256 \), and \( \omega = 3600 \) rpm,

\[ H = (0800h + 07FF \ (L_{i+1} - L_i) \left( \frac{60 \times N}{T \times w \times 256} \right)) \]

\[ = 0800h + 07FF \Delta L \cdot \frac{1}{300} \]

\[ = 0800h + 6.83 \Delta L \]

\[ = 0800h + 8\Delta L. \]

The value, 8, is preferred because three 'ASL' statements can do the multiplication in very little time. Due care has to be taken in shifting signed error signals.