A Platform with Six Degrees of Freedom

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A PLATFORM WITH SIX DEGREES OF FREEDOM

By D. Stewart*

This paper describes a mechanism which has six degrees of freedom, controlled in any combination by six motors, each having a ground abutment. It is considered that by its particular arrangement, this mechanism may form an elegant design for simulating flight conditions in the training of pilots. Unlike most simulators, it has no fixed axes relative to the ground, and therefore within the limits of amplitude of the design it can truly simulate the conditions of banking by carrying the simulation of control surfaces into the axes of the new attitude.

Variations in control arrangements are described and their respective design merits considered.

Other possible uses for this mechanism are mentioned, including automation of production.

INTRODUCTION

IN THE SEARCH for a suitable means for simulating flight conditions for the safe training of helicopter pilots, the design of a mechanism has been established having all the freedoms of motion within the design limitations of amplitude and capable of being controlled in all of them simultaneously. A result of this exercise has been to release the imagination to conceive many other uses for such a mechanism.

Modern developments in passenger transport, whether they are in air, sea or space, have subjected man to mixed accelerations beyond any previously known. The effect of speed on the reactions of a human being are negligible compared with those caused by the change of direction or speed and when a human control link is introduced into a control chain, the effect of acceleration upon his actions is of great importance.

It is dangerous to assume the performance of a complex control system without checking that the design of each part stands up to practical usage. In some studies which have been carried out it has been found that to take into consideration only some of the forces, including the human frame, that may occur on the control instruments, may lead to spurious conclusions. The reason why experiments have been conducted in the past using only a limited number of the factors likely to be involved has been due in the main to the lack of a test platform capable of being controlled in all degrees of motion in accordance with a pre-arranged programme.

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In this paper a mechanism is described which it is suggested may be used:

(*a*) As a vehicle for representing a body in space subjected to all the forces which may be met with in its voyage.

(*b*) As representing a platform held stationary in space mounted on a vessel such as a ship which is subjected to the random movements of the sea.

(*c*) As a platform for simulating the actions of the helicopter as driven by its pilot, or

(*d*) As a support for a helicopter which is capable of being driven by the pilot, random actions being applied to the supporting platform as prescribed.

(*e*) As any vehicle which is subject to control by a human being.

(*f*) As a basis of design for a new form of machine tool.

(*g*) As a basis of design for an automatic assembly or transfer machine.

DESIGN AIMS

There are many possible designs for providing the six degrees of motion; for instance, one obvious method would comprise a three-axis gimbal superimposed upon a three-axis linear slide system. To incorporate rigidity and quick response in this type of solution, when high performance or large amplitudes are required in all of the six motions, generally presents serious design problems and is expensive.

Design aims were to achieve the most simple and cohesive design with the highest capabilities in a wide range of applications.

Design aim	*Purpose*
(1) The use of not more than six motors.	To avoid redundancy and reduce cost.
(2) Each motor reacting on the foundation.	To avoid interaction between motors.
(3) Each motor operates directly on the same load.	To achieve the maximum performance for a given power source.
(4) High pay load/structure weight ratio.	To achieve the maximum performance from power available.
(5) Each motor identified with one motion.	Simplicity of control.
(6) Low friction motions.	To reduce power losses and to obtain high response.

When these design aims were studied it became apparent that aim 5 was basically incompatible with the aims 2–4. Therefore aim 5 was abandoned in favour of achieving the other aims and thereby gaining in structural rigidity and system response.

The following description is of a mechanism which does comply largely with these aims. The failure to meet aim 5 is a loss in very simple mechanism usages, but when the input or output information is complex, the lack of simplicity in transferring the information to the mechanism is of less importance.

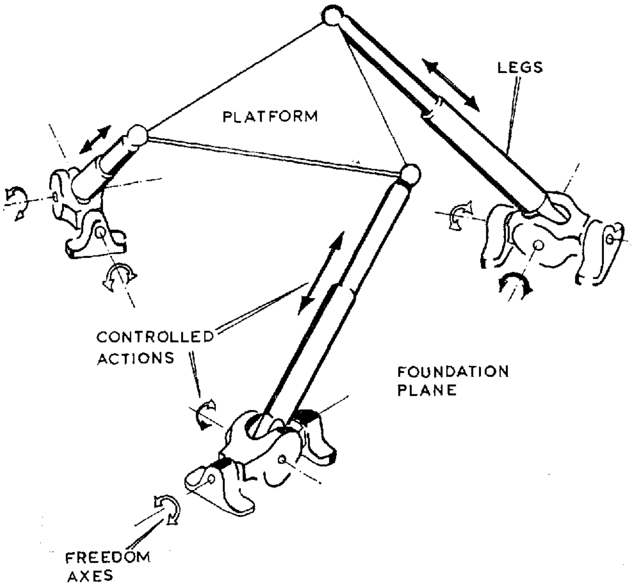

Fig. 2. General arrangement

DESCRIPTION OF MECHANISM

The six-degrees-of-motion platform is, as the name implies, capable of moving in three linear directions and three angular directions singly or in any combination. It comprises a triangular plane called the platform, of which each of the three corners is connected through a three-axis joint to one of three legs (Fig. 2). Each leg is connected to the ground by a two-axis joint. One of these axes is normal to the leg and is provided with a means for control. The other axis is normal to the first and is not provided with a means for control. Each leg also has controllable means for extending its length. In this manner, the platform attachment point to each leg can be controlled by polar co-ordinates relative to the ground-fixing-points in the plane containing the leg. The three legs when in the mean position are arranged so that each leg is contained in a plane that is tangential to a circle which contains the three points of the platform, Fig. 3; each point of tangency occurs at the point of attachment of a leg to the platform.

The operation of each leg is to control the platform attachment point within the plane previously defined and to enable this plane to accommodate itself on other considerations.

To describe how to achieve these requirements, first let the functioning of one leg be considered alone (Fig. 4). Various methods can be employed for achieving polar co-ordinate control of the leg and one method will be described by way of illustration.

The leg can consist of one hydraulic jack that within the stroke of the jack will control its length. The outer end of the piston rod is connected to the platform by a three-axis joint, and the cylinder end is connected to the foundation by a two-axis joint. A second jack has one end connected by a single-axis joint to the outer cylinder end

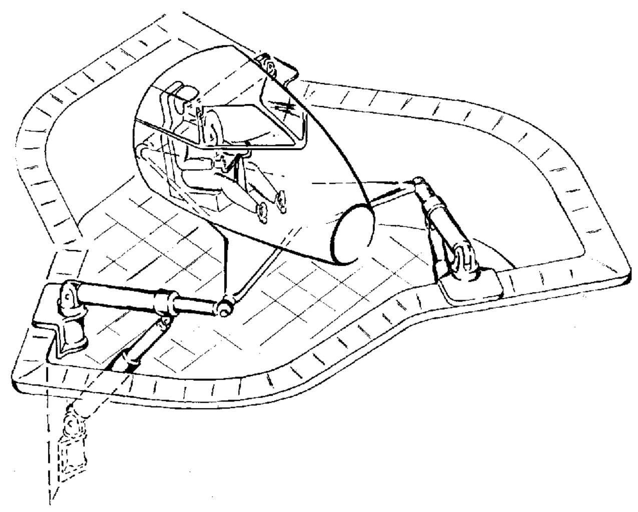
Fig. 1. Pictorial view

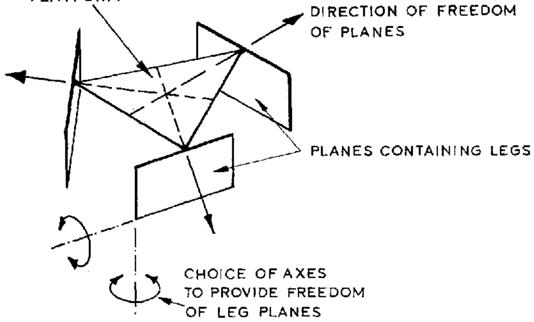

Fig. 3. Diagram of leg planes

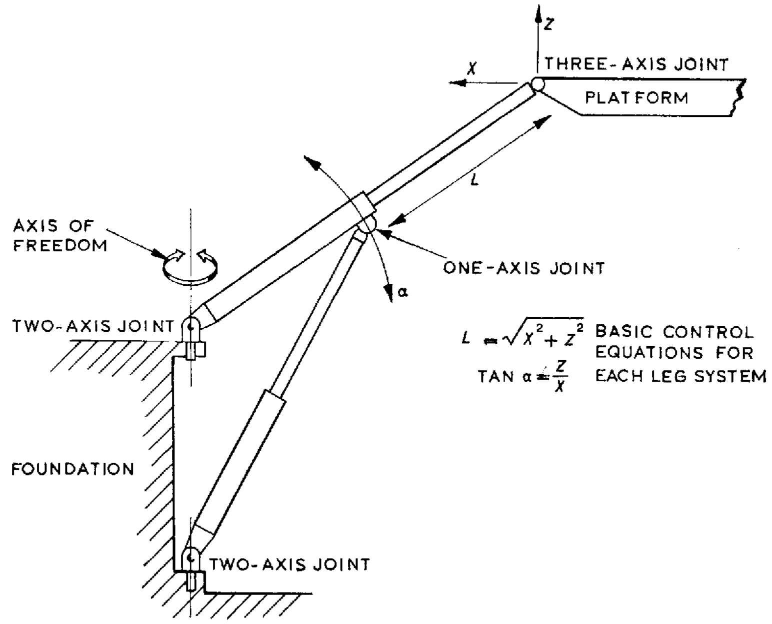

Fig. 4. General arrangement of single leg system

of the first jack and the other end to the foundation by a two-axis joint so that it is able to control the angle of the first jack with respect to the foundation. It will be noticed that the two jack foundation connections have one common axis and the remaining axes parallel to each other. The common axis is not controlled within the single leg system but the plane containing the leg can rotate about it, thereby permitting a three-axis motion on the platform support joint.

If the platform is supported by three such legs attached to the three points as described, each lying in a plane tangential to a circle containing the three points, the position in the direction of no control of any one leg is determined by the controlled position of the other two legs. Thus where each leg defines the position of its appropriate platform point in two dimensions, conjointly they will define the three points of the platform in three dimensions. To illustrate this point Fig. 3 shows a platform supported by three planes representing the legs, each plane being free to pivot about one edge.

In this manner position and attitude of the platform can be defined, hence the six degrees of motion can be determined, for if the three points are moved similarly in the X–Y–Z co-ordinates, the three linear motions are obtained and if moved in the X–Y–Z co-ordinates differentially then the three angular motions are obtained (Fig. 5).

KINEMATIC ANALYSIS

The following kinematic analysis shows the validity of the mechanism in that it satisfies the following requirements:

(*a*) When the controllable axes are active, the platform must be controlled in six degrees of motion.

(*b*) When the controllable members are stationary the platform must have a corresponding fixed position.

Let the platform and foundation each be as one member and each leg as two members, the mechanism consists of a total of eight members and can be illustrated diagrammatically as Fig. 6*a*. The joints are indicated by the circles and total nine in number. If the degrees of freedom in the joints are now inserted into the circles, there will be

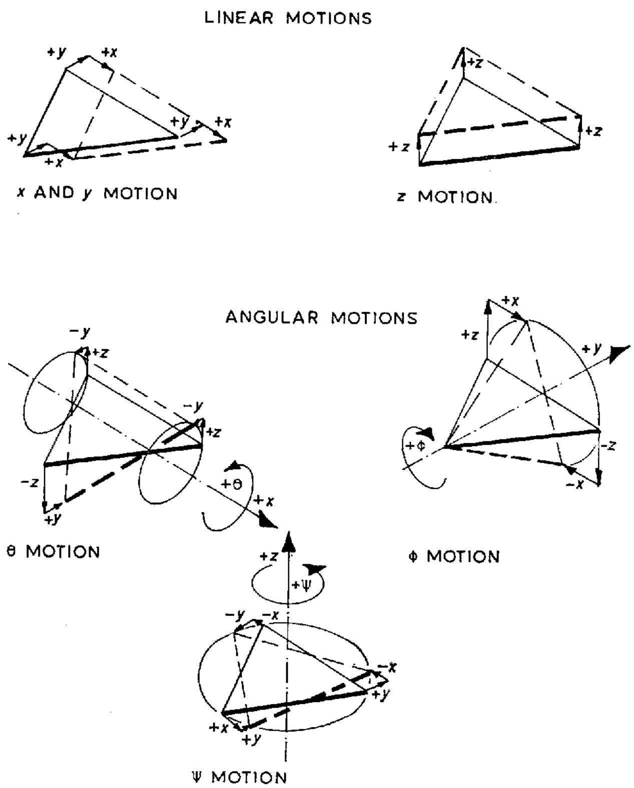

Fig. 5. Illustrating the six motions of the platform

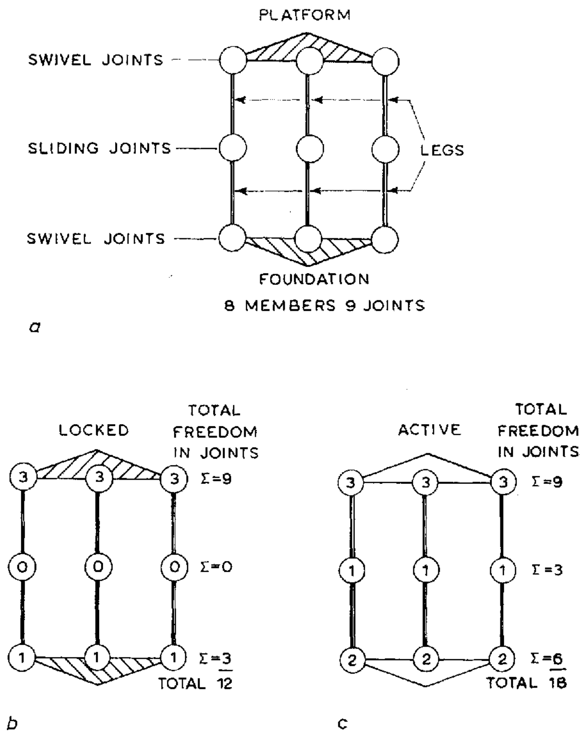

Fig. 6. Kinematic diagram of mechanism

two cases, one when the mechanism is locked, the other when active, Figs 6*b* and 6*c*.

It will be seen that when locked, the mechanism has a total of twelve freedoms in the joints and when active a total of eighteen. In accordance with Grodzinski and M'Ewen, in a paper presented in 1953 to the Institution (1)*, the resulting degrees of freedom in a mechanism can be calculated from the number of links (members), the number of joints and the freedoms within the joints.

Thus $$F = 6(n-1)-\sum_{1}^{g}(6-f)$$

where F = resulting degrees of freedom in system
f = number of degrees of freedom of joints
n = number of members
g = number of joints.

In this application where the controlled joints may be locked the expression may be written as:

$$F = 6(n-1)-6g+f_1$$

for clarity of comparison, where f_1 = total degrees of freedom in all joints.

By inserting the numerical values of the mechanism as described, we get:

$$F \text{ when active } = 6(8-1)-6\times 9+18 = 6$$

$$F \text{ when locked } = 6(8-1)-6\times 9+12 = 0.$$

These results show the validity of the design in that it satisfies the specified requirements for the mechanism.

* *References are given in the Appendix.*

MOTION ANALYSIS

It has previously been described how each of three legs is controlled by polar co-ordinates to position a platform supported by these legs. We will now relate the amplitude of movements of the legs to the amplitude of the displacement and attitude of the platform.

As already stated, similar movement of all three legs in the $X-Y-Z$ co-ordinates results in $X-Y-Z$ motion of the platform and differential movement results in attitude movement of the platform. It will therefore be apparent that the linear displacements of the platform are directly related to the amplitude of movement of the legs, whereas the amplitudes of the angular attitudes will be proportional to the spacing of the three points on the platform relative to the linear motions of the legs. It follows, therefore, that the smaller the platform size relative to the stroke of the legs, the larger the angular motions.

The positioning of the earth point relative to the platform support points will influence the shape of the total envelope of movement. As already defined, the plane containing the legs when in the mean position contains the earth and platform support points, and now a choice of positioning the earth point within the plane can be made.

It will be seen that if the earth point is positioned directly below the platform support point (Fig. 7) the envelope of movement is confined above the plane containing the three earth points and the amplitudes will be larger in the X and Y plane than in the Z direction. Alternatively, if the earth points are positioned in the same plane as that containing the three platform support points (Fig. 8) the envelope of movement lies above and below this plane and the amplitude will be larger in the vertical (Z) direction than the horizontal (X–Y) plane.

It will be seen that in the first condition the legs are in phase with each other so that the envelope of movement of one leg can be taken as the amplitude for the platform,

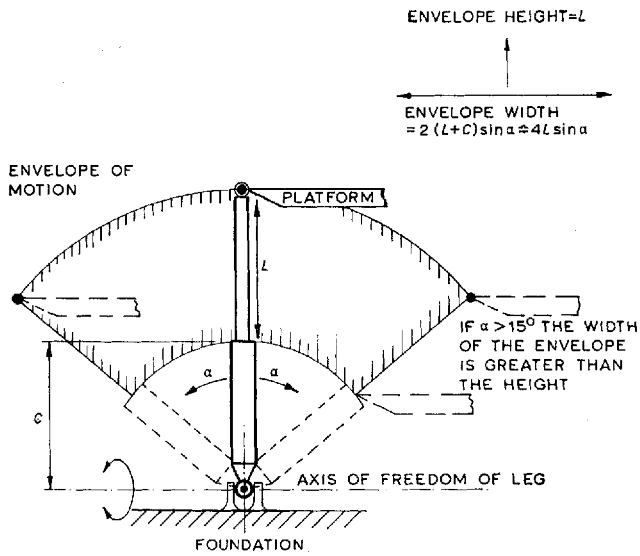

Fig. 7. Arrangement of platform, with legs vertical

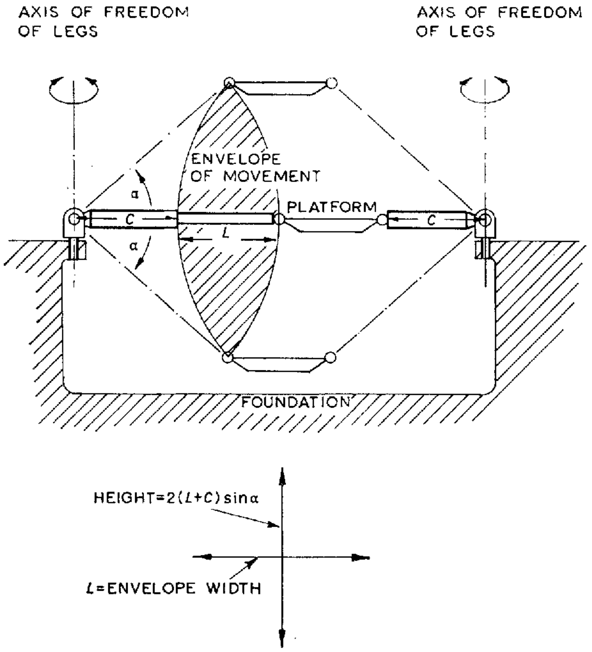

Fig. 8. Arrangement of platform, with legs horizontal

whereas in the second condition the legs are in opposition (that is, when one leg is extended the other is retracted).

The envelope of the motion of the platform is therefore defined by the overlap of two legs, one leg defining one side of the envelope, the other leg the opposite side; also, it will be noted that the axis of freedom for the plane containing the leg is horizontal in the first case and vertical in the second.

LIMITATIONS OF AMPLITUDE

Movement of the platform becomes restricted when any one platform support point is coincident with the axis of freedom of any one leg system; when such a condition is reached there is only a two-axis control of that support point.

Instability occurs if the centroid of the platform support points and the two ends of any one leg fall in line. This will occur in such a case as Fig. 9 when a particular pitching amplitude is reached, and in an arrangement as Fig. 10 when a particular azimuth is reached.

There is, of course, the normal amplitude limit set by the maximum extension and contraction of each jack.

CONTROL MEANS

To arrange for the platform to be operated in accordance with a pre-determined programme involving linear or angular accelerations or a combination of both, the necessary signals can be given to the various jacks in accordance with the input requirements to control the platform in the required direction.

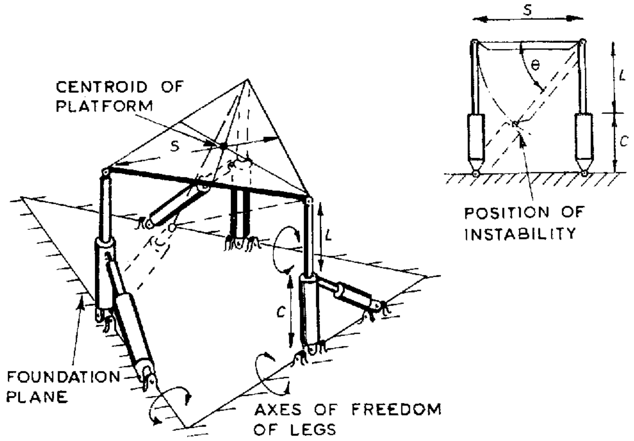

Fig. 9. Showing position of instability (vertical legs)

The equations for the related movements of the various power jacks will be known and stored in a master-computer so that any desired acceleration of the platform when fed into the computer would automatically be translated into the component movements of the various jacks. These movements would then combine to give the required movement to the platform. Each component jack would feed back to the computer, positional and velocity information to complete its servo loop control.

This provides a unique situation whereby this mechanism can truly simulate an accelerating body in any direction and attitude; e.g. an aircraft in flight.

The mechanism does not impose on the platform any axes of motion which are earth fixed, as do other systems.

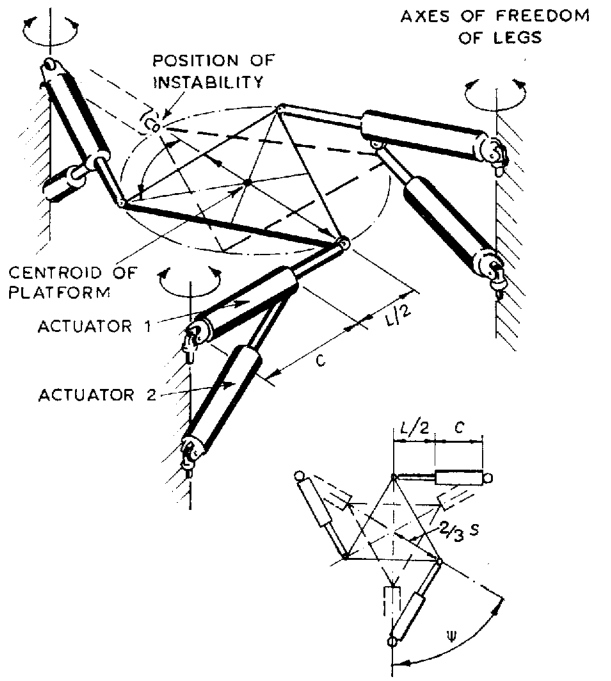

Fig. 10. Showing position of instability (horizontal legs)

It is therefore possible to control the movement of the platform in any chosen co-ordinate system, such as body fixed, or earth fixed co-ordinates or any combination. The former system of motion is that performed by most vehicles, and in particular aircraft where pitch, roll and yaw axes remain fixed within its structure as do also the co-ordinates of lift and thrust.

Where it is required to stimulate human reactions, or activate sensors mounted within a vehicle by the correct accelerations due to its motion, it is essential that the motion of the simulator mechanism has the same characteristics as those of the vehicle.

It has previously been shown that provided the position of the three corners of the platform can be controlled in X–Y–Z co-ordinates relative to the foundation, a fixed attitude and position of the platform can be obtained. It follows, therefore, that if the computations for the required motion of the platform in the chosen co-ordinate system are resolved into terms of X–Y–Z co-ordinates of each leg then entirely uninhibited motion of the platform can be obtained within the amplitude of the mechanism.

The following equations refer to the length and angle of a leg relative to its mean position, to establish the corners of the platform in terms of fixed X–Y–Z co-ordinates.

Assuming an arrangement as shown in Fig. 10 and making the mean position when the actuators No. 1 are in plane with the platform then referring to Fig. 11 and using the following notation:

L = length of leg (actuator No. 1)
α = angle of leg to foundation (actuator No. 2)
l = initial length of leg (constant)
β = initial angle of leg to the X axis (constant)

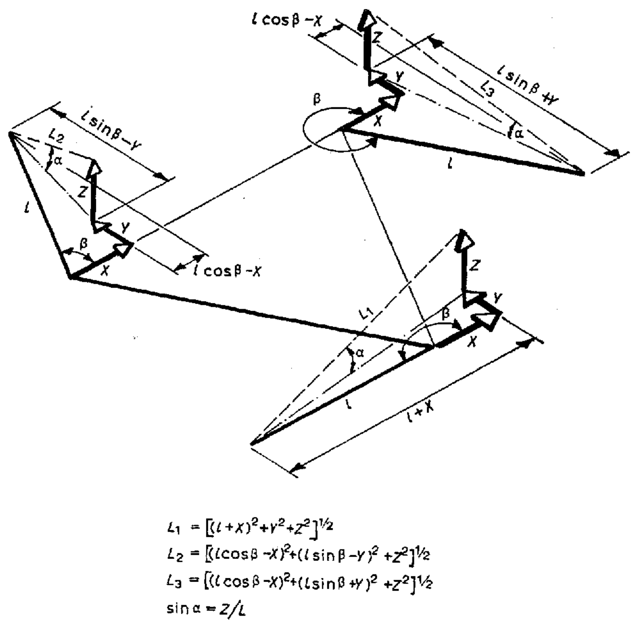

Fig. 11. Control geometry

The following general expression is obtained:

$$L = [(l \cos \beta - X)^2 + (l \sin \beta - Y)^2 + Z^2]^{1/2} \quad (1)$$

Now in a practical example where the platform is made an equilateral triangle as shown in Fig. 11, the three legs L_1, L_2 and L_3 have associated angles β_1, β_2 and β_3, which will have the following values:

$$\beta_1 = 180^\circ;\ \beta_2 = 60^\circ;\ \beta_3 = 300^\circ$$

Putting these values in equation (1) will give equations for each leg as follows:

$$L_1 = [l^2 + 2lX + X^2 + Y^2 + Z^2]^{1/2} \quad . \quad (2)$$

$$L_2 = [l^2 - lX - 1{\cdot}73lY + X^2 + Y^2 + Z^2]^{1/2} \quad (3)$$

$$L_3 = [l^2 - lX + 1{\cdot}73lY + X^2 + Y^2 + Z^2]^{1/2} \quad (4)$$

$$\sin \alpha = \frac{Z}{L} \quad . \quad . \quad . \quad . \quad (5)$$

For any platform motion system the required X–Y–Z co-ordinates of each corner will be the sum of the linear displacements of that point as a result of linear movement and angular movement of the platform.

If x–y–z = the linear displacement of the corners due to linear motion of the platform;

and fx, fy, fz = the linear displacements of the corners due to angular motion of the platform

then
$$X = x + fx$$
$$Y = y + fy$$
$$Z = z + fz$$

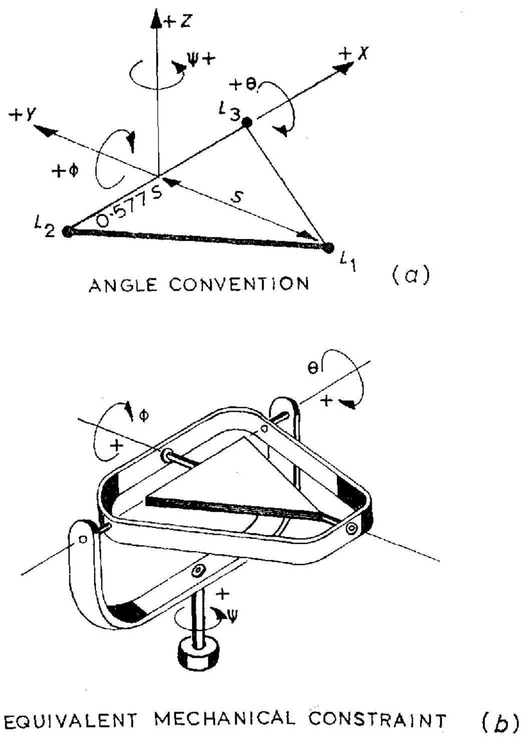

Fig. 12. Control geometry angular motion

If the platform linear motions (x–y–z) are earth-fixed then they can be inserted directly into equations (2)–(5). If they are on platform-fixed co-ordinates then computations taking into account the platform attitude will be required. These computations are lengthy and will not be dealt with here.

The linear motions of the corners of the platform as a result of angular motion (fx–fy–fz) can be equated as follows. Referring to Fig. 12*a*, which identifies the selection of axes relative to the corners of the platform, it will be seen that the axes do not coincide at the centroid of the platform. This has been done for mathematical convenience only and enables each platform point to be independent of one angular motion resulting in a more simple analysis. In Fig. 12*b* will be seen the equivalent gimbal constraints that produce the same axes convention as those selected, and in Fig. 13 are shown the excursions of the three corners of the platform as a result of compound angular motion.

The following equations give the relevant fx–fy–fz for the three corners in terms of the three angular motions θ, ϕ and ψ:

$$L_1\begin{cases} fx_1 = +S\sin\psi\cos\theta & (6)\\ fy_1 = +S(1-\cos\psi\cos\theta) & (7)\\ fz_1 = -S\sin\theta & (8)\end{cases}$$

$$L_2\begin{cases} fx_2 = +0{\cdot}577S(1-\cos\psi\cos\phi+\sin\phi\sin\theta\sin\psi) & (9)\\ fy_2 = -0{\cdot}577S(\sin\psi\cos\phi+\sin\phi\sin\theta\cos\psi) & (10)\\ fz_2 = +0{\cdot}577S\sin\phi\cos\theta & (11)\end{cases}$$

$$L_3\begin{cases} fx_3 = -0{\cdot}577S(1-\cos\psi\cos\phi+\sin\phi\sin\theta\sin\psi) & (12)\\ fy_3 = +0577S(\sin\psi\cos\phi+\sin\phi\sin\theta\cos\psi) & (13)\\ fz_3 = -0{\cdot}577S\sin\phi\cos\theta & (14)\end{cases}$$

The combination of equations (6), (7) and (8) with equation (2) will give the control equation for leg 1 and similarly with equations (9), (10) and (11) with equation (3) for leg 2; and equations (12), (13) and (14) with equation (4) for leg 3.

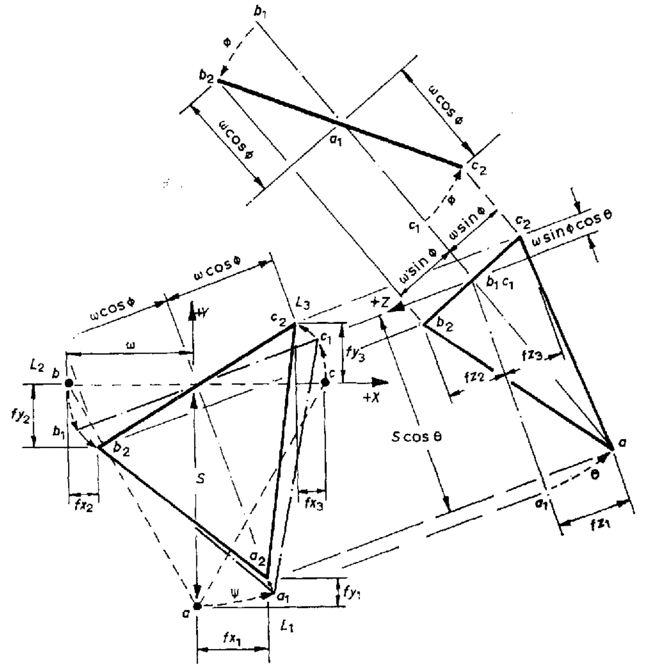

Fig. 13. Control geometry angular motion

Levers

The extending leg amplitude can be increased if the jack is replaced with an articulated leg and the jack operating part way along the outer limb. If the joint for the articulated leg is in the middle of its length then theoretically it is possible to get the amplitude of the outer point from zero to the maximum. In practice, it would be reduced by a small amount, but in any event it is likely that larger amplitudes would be achieved than with the linearly extending leg, where the amplitude approximates from half length to maximum. Note that this system would alter the geometry so that the leg would now be controlled by two angles instead of one angle and a length (Fig. 14).

MECHANICAL DESIGN CONSIDERATIONS

One method of controlling the legs in polar co-ordinates within a plane has been illustrated by using two hydraulic jacks (Fig. 4). Other methods will now be discussed.

Screw jacks

The piston jacks as illustrated in Fig. 4 can be directly replaced by screw jacks. This could give the advantage of a longer stroke for a given size.

Rotary actuator

The jack controlling the angle of the leg could be replaced with a hydraulic rotary actuator or electric motor. This would reduce the number of foundation fixings, but the remaining jack would be subjected to a greater bending moment.

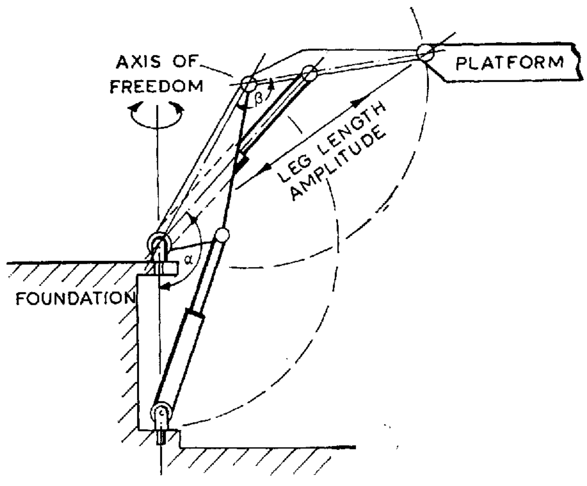

Fig. 14. Articulated levers

Linear co-ordinate control

The original choice of 'control' for the leg system was by polar co-ordinates but the platform support point can be just as effectively 'controlled' in linear co-ordinates as shown by Fig. 15. In this arrangement, a system is provided which is a hybrid of the arrangements shown in Figs 9 and 10. The main advantage of this arrangement will be in its inherent rigidity due to the true triangulation of the whole system. There will be no bending moments in any of the members apart from the possibility of those due to strut eccentric loading. A further advantage may lie in the modified control equations required. The equations for the horizontal legs will be the same as those outlined in the section on control means and the sin α term required by the other actuators will be replaced by

$$L_4 = [(X^2+Y^2+(l+Z)^2]^{1/2}$$

for all the vertical legs. The envelope of movement will be a combination of the amplitudes shown in Figs 7 and 8 and will result in an approximately cylindrical form of envelope.

The kinematic analysis of this arrangement requires special treatment in that three members now coincide on a single joint with three degrees of freedom. The practical design of the mechanism actually has the three members coincident on this joint, but for the analysis the joint must be considered as two separate ones each with three freedoms connected by the member forming the platform (2). The resulting kinematic diagram will now be made up of 14 members and 18 joints with a total of 36 and 30 freedoms respectively for jacks operating and locked. When these figures are applied to the formula, correct resulting mechanism freedoms are obtained.

The arrangement just described is likely to have much value in systems where the greatest degree of rigidity and response is of more importance than amplitude.

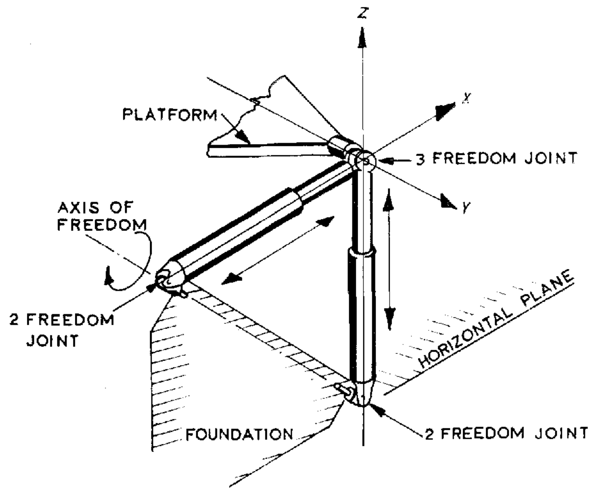

Fig. 15. Linear co-ordinate control

Strength

Since each leg has one free axis at the earth point, no forces can be experienced laterally to the plane of the leg. It is therefore only necessary to provide resistance to bending within the plane of controlled motion of each leg as in Figs 9 and 10, apart from the usual consideration given to loaded struts. This allows a favoured distribution of material in each leg.

When the platform is in a locked position, the stability of position will depend on the quality of the joints in the system. The platform attachment points, which are three-axis pivoted joints, are the most complex, and in order to maintain a high power efficiency special considerations must be given to their strength-to-weight factor. Play in these joints does not have any magnification on the platform position and attitude, because it will have a unity relationship with platform position, together with a $1/R$ effect on the attitude, where R is the radius of the circle containing the platform. In Figs 9 and 10 arrangements of the joints on the foundation will be more critical with regard to the stability in that any play will result in magnified dynamics at the platform, but here weight and size will be of less importance from the power point of view and ample rigidity should be readily achieved.

The stability of the platform position will also depend on the rigidity of the actuators but here it would require a specific choice of actuators for given loading and accelerations before the resultant rigidity could be qualified.

CONCLUSIONS

The mechanism described consists of an eight bar spatial linkage which it would seem has so far been overlooked in the many published analytical treatises (1). It is considered that it could take its place as a fundamental concept in spatial linkages for the basis of economical machine design in a similar way to that of Watt's and Stephenson's six bar linkages which paved the way in planar mechanisms. Thus it is to be expected that a very large number of applications will be found for it when its properties become generally appreciated.

The most obvious applications are those relating to various types of simulation as mentioned in the introduction. It may well be, however, that the greatest impact will be made where full universal motion is desirable.

Other uses come to mind such as general handling problems in cargo manipulation, in the medical field, and in earth removal.

APPENDIX

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Communications

Mr G. H. Meier (Zurich)—This new method of obtaining a platform with six degrees of freedom cannot be compared with the method using a three-axis gimbal superimposed upon a three-axis linear slide system, as this method is no longer worth considering when such a platform is needed, because of its large size, weight, complexity and lack of high performance characteristics; whereas the new concept is light, relatively simple, compact and capable of high performance. Obviously there are technical difficulties that will have to be overcome to realize the full potential of the design, but it is thought that these can be solved by careful design. This applies especially to the servos controlling the actuators, where accuracy and high performance are required, as the stability of each loop is dependent on that of all the other loops together.

We do not propose to discuss in detail the basic theory of the design of the platform, as the author has done this so clearly that there is not much left to discuss, except about the points of instability. With vertical legs it would appear that the position of instability limits the maximum angle of pitch but still leaves a large envelope of travel in which this condition is not reached. With horizontal legs the position of instability cannot be eliminated. It could happen that all three actuators fall in line with the centroid of the platform, then the table is unstable in angular motion and forces could be exerted on the platform causing buckling if a signal is given for rotation in this axis. The extent of the instability will be governed by the misalignment of the actuators with respect to the platform. The chance that the platform could rest in this position and such a motion occur is very slight but the danger always exists.

The applications for this type of platform are obviously expensive as it requires a computer and six servos, and their cost will depend on the accuracy and performance required; the most obvious uses are those relating to simulation. In the other fields they are limited because of the expense involved, but there are fields where it is possible to use such a platform and these could be in the machine tool and medical field.

Of the different variations discussed, the method using linear co-ordinate control would appear to have the best chance of further development as it has the advantage of inherent stability along with a light working platform and thus is capable of high performance. These characteristics make it particularly attractive to the machine tool industry as a working table for machines. It could be used on large co-ordinate milling machines where complicated contours have to be machined, or on small machines with a rotating table mounted on the platform to give 360° rotation. The main advantage is that one has a variable centre of rotation and this can be programmed to give the shape required. Whether one can machine concave as well as convex shapes will naturally depend on the tool itself. The accuracy will naturally depend on the accuracy of the servo and the rigidity of the table.

Another application could be in hospital ships or liners in the medical field or as a gun platform aboard a warship. It would have the effect of not only eliminating the rotational motions but of damping the linear motions. This would mean that a doctor would be able to perform delicate operations as he could work on a stabilized platform. When used as a stabilized gun platform the damping of the linear motions should result in greater accuracy. The main limitation in this case is the inertia of the structure mounted on the platform as accuracy and performance are related to this.

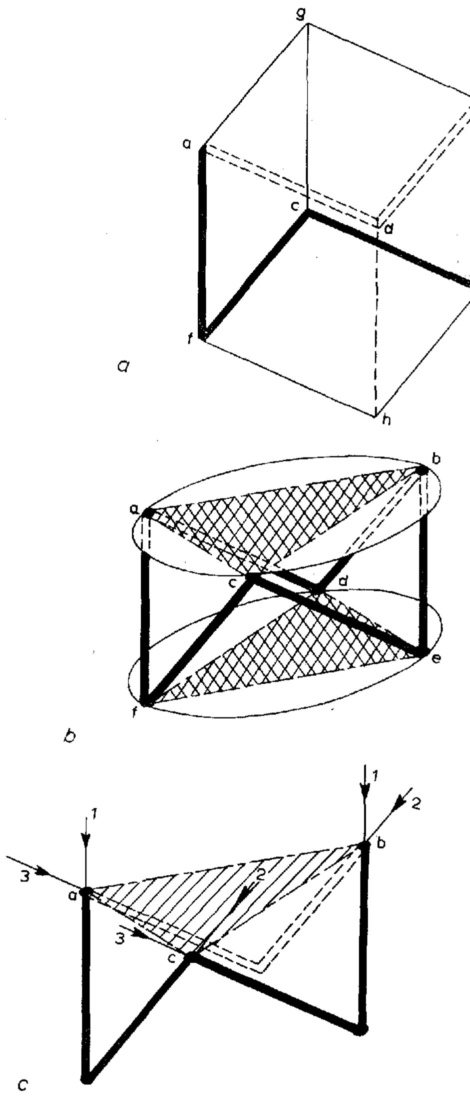
Mr G. P. Easten, M.A. (Wickham)—I have read this paper with interest because it describes an extension and a refinement of a device that I have considered as a possible means of aligning a radio or radar aerial. In such an application, linear motions are not important but, as with Mr Stewart's platform, the elegance and simplicity of the mounting is to some extent vitiated by the complexity of the control mechanism, and it would be interesting to know more about how Mr Stewart is thinking of dealing with this part of the invention. He does not indicate whether the awkward equations would be solved digitally or by analogue computer.

A method that springs to mind is to construct an exact scaled-down model, force it to perform the motions required and servo the full-scale jacks from linear pick-offs on the model jacks. Since only some of the motions, e.g. the three rotations, need be applied to the model platform, if the remaining motions are applied to the foundation of the model the design and construction of such a machine might be cheaper than that controlled either by an analogue or digital computer.

Is Mr Stewart working on anything like this, or what alternative has he in mind?

Mr V. E. Gough, B.Sc. (*Member*)—My attention was drawn to this paper by the photographs of the six linear jack system in (3). We have used this system with success for many years (4) (5). As stated in (4), I devised the six linear jack system (author's eight bar system) in 1947, designed the tyre test machine in (5) in 1949, and this was operational in 1954–55. We used screw jacks for simplicity. Since the publication of (5) we have fitted digitally controlled motor drives to the jacks, electronic recording to the load cells, and a modern electronic version of specialized instrumentation to study tyre-to-ground forces and movements, which we have also developed during our tyre studies.

In our version of the six jack system we avoided the use of a common joint shown in Fig. 15 of the paper and



a Fundamental cube with basic framework in double lines.
b Arrangement of jacks based on fundamental cube of jacks ad, af, bd, be, ce, cf.
Upper plate abc, lower plate def.
c Disposition of load gauges based on fundamental cube.
Load gauges are parallel in pairs a1, b1, b2, c2, c3, a3 and are on the basic framework extended. The triangle abc is the subframe carrying the axle. The top ends of load gauges are attached to the upper platen.

Fig. 16. Principle of machine construction

attached each jack separately to the upper platform. In point of fact, the universal joint systems attaching the jacks to the platform are identical to those attaching the jacks to the foundation.

Reference (5) gives the method of calculating the jack lengths. We have a fully computed table from which we read off required values. An appendix to (5) gives the process used for computing reactions in various co-ordinate systems from the load gauges; we have computer programmes to expedite this work. The load cells are arranged in a configuration related to the 'basic cube', which led me to the six jack system. The guiding principle which I used in devising the original jack system was symmetry or orthogonality. The relationship of any one jack to the other five must be the same whichever jack was chosen—after a lot of thinking the cube of Fig. 16 was obvious!

I would further amplify the point made by the author at the top of p. 376, where he says that it is possible to control the movement of the platform in any chosen co-ordinate system. The platform can be set in any attitude and moved in any (unrelated) direction. This point and its importance became clear to me when I compared our universal tyre test machine (Fig. 17) with machines built on conventional slider and gimbal systems which I have seen in the U.S.A.

Our experience with the device of (4) and (5) is strongly in favour of the six linear jack system, to which Fig. 15 relates (but which is more clearly illustrated in reference (3)). However, I prefer our particular version shown in the accompanying figures; a matter of detail perhaps, but such details are important. The system is inherently stable and rigid and capable of large movements.

We have discussed applications of this system with computer firms at various times during the last three or four years, and it is clear that the system is thoroughly amenable to computer-cum-servo control. In passing, it will be noted that one scheme was mentioned in (5). In the very early days I even wondered whether a servo control system from a scale model six jack system might be acceptable to those who do not like mathematics—the full scale device following the motion of the model.

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(4) Gough, V. E. 'Contribution to discussion to papers on research in automobile stability and control and in tyre performance, by Cornell staff', *Proc. Auto. Div. Instn mech. Engrs* 1956–57, 392.

(5) Gough, V. E. and Whitehall, S. G. 'Universal tyre test machine', *Proceedings, Ninth International Technical Congress F.I.S.I.T.A.* May 1962, 117 (Institution of Mechanical Engineers).

Professor K. H. Hunt, M.A. (*Member*)—I commend the author on his use of constraint criteria associated with the names Grübler and Kutzbach (described under the section on kinematic analysis). The fact that it is possible to study the mobility of a mechanism or a mechanical

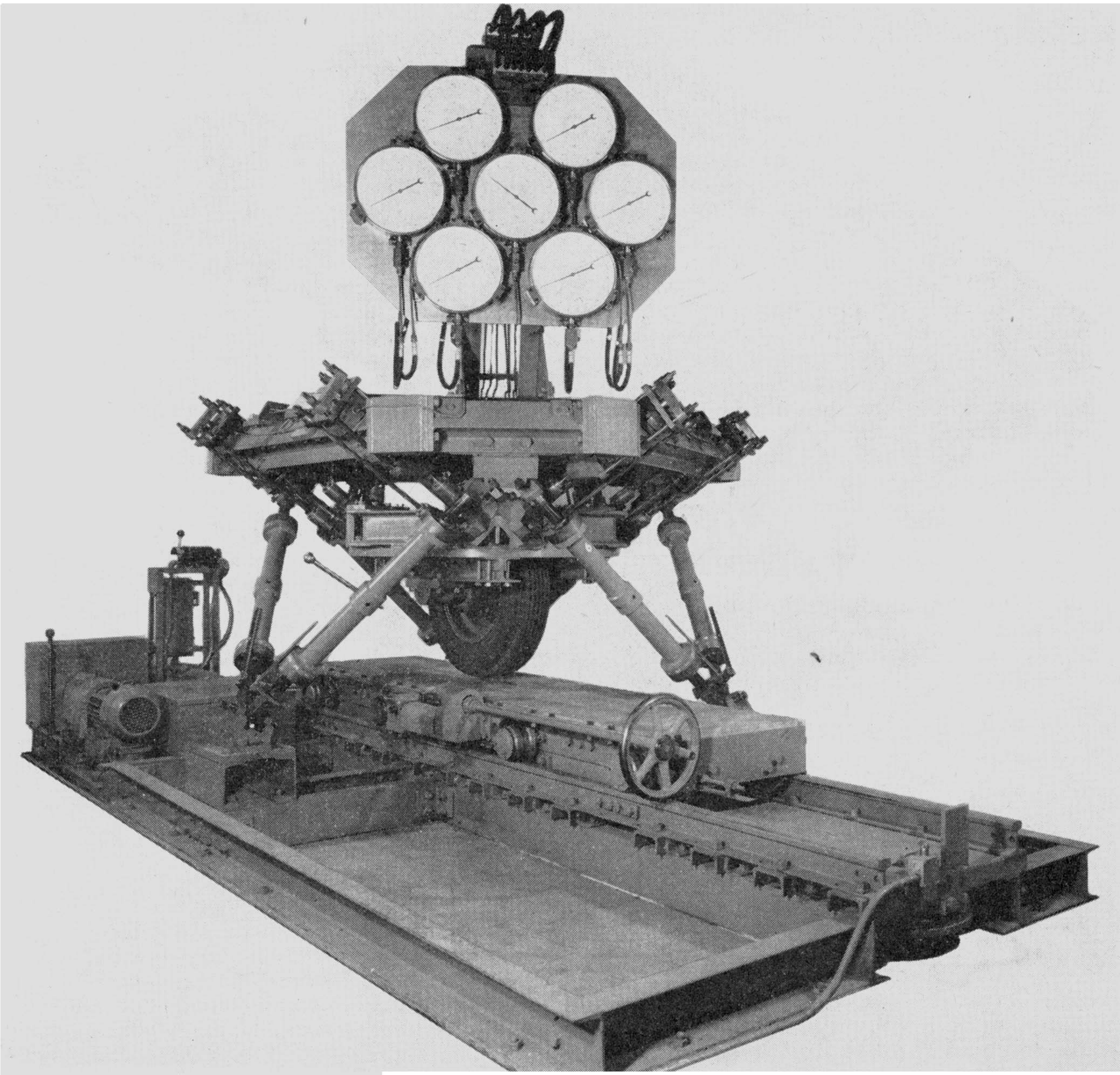

Fig. 17. Photograph of machine

connection systematically is often overlooked by designers, and this paper must be one of the rare instances of a British publication actually demonstrating the usefulness of the criteria, even if only as verification.

Constraint and mobility criteria commonly find application to mechanisms that aim to produce a certain output motion from a given input; but here the author is concerned with the degree of connection between two members of a multiple-loop chain. The design described is quite simple and reasonably symmetrical, and the calculated degrees of connection are correct. But it is not true to say that the degree of connection between two members in a kinematic chain always agrees with the value F of the overall number of degrees of freedom, or degree of mobility, of the chain as a whole. There are traps for the unwary that can only be avoided, and understood, by a more widespread appreciation of the subject of mobility and degree of connection. The writer feels he should take the opportunity to mention the recent paper of Harrisberger*, which quotes, amongst an extensive list of references, some useful sources of information; also

* HARRISBERGER, L. 'A number synthesis survey of three-dimensional mechanisms', *Trans. Am. Society of Engineers* (Journal of Engineering for Industry) 1965 **87** (Series B), No. 2, 213.

the work of Voinea and Atanasiu* and of Manolescu and Manafu†, all of whom are concerned with the problem of logical and systematic appraisal of special geometrical instances where the general criteria do not appear to hold, as, for instance, in the unstable configurations mentioned by the author. It is probable that, in the event of the author's ideas and designs being further developed, as he hints at in his conclusions, a more exhaustive study of the conditions of constraint and mobility would be well worth while.

Mr P. Murdoch (*Member*)—The particular arrangements of jacks mentioned probably are intended to simplify the control equations. However, this simplification can be valid only over a very limited range of movement and, if full co-ordinate conversion is provided in the computer, there may be advantages in choosing a more symmetrical, fully triangulated layout. For example, the equivalent of the vertical leg system of Fig. 9 could be a base triangle with two jacks attached at each apex, the other ends of the jacks being attached to the triangular controlled plane. In datum position, this controlled plane would have each apex vertically over the mid-point of a side of the base triangle.

In the simulator application, the presence of computing equipment makes the co-ordinate conversion problem acceptable. In some of the other possible applications, however, it may be desirable to provide a mechanical arrangement for continuous co-ordinate conversion, to simplify the control arrangements.

Mr K. H. Nicholls, O.B.E. (*Associate Member*)—Claim is made in the section on control means, p. 375, that the mechanism provides a unique situation whereby it can truly simulate an accelerating body in any direction and attitude, e.g. the flight of an aircraft. The sense of sustained acceleration cannot be depicted in the system thus continued. Curved course flight banking or vehicle cornering is precluded.

Whilst three translation motions are added to what may be called conventional three-axis tables, this does not cover maintained acceleration upon the human frame but only embraces, say, limited eccentric yaw, surge, swing and bounce as is experienced in vehicles moving in a mean straight course at mean constant velocity over 'bumpy ground', e.g. ship's deck above metacentre.

The system offers a marked but limited advance over conventional three-axis tables but loses 'round and round' centrifugal training which is a required feature in many applications.

Mr D. J. Thomas (Bedford)—These comments refer only to the possible use of the platform for flight simulation and it is necessary to ask first of all—'Are six degrees of freedom really worth while?' The only way of reproducing all the rotations and accelerations which occur in flight, without introducing any false effects, is to follow exactly the same path in space as does the real aircraft. Unless one is simulating only the smallest of perturbations from the hover or straight-and-level flight no practical system is capable of meeting this requirement. One must accept some limitations and approximations. Rotations can be adequately represented but sustained thrust and centrifugal accelerations are extremely difficult and the limits are reached rapidly.

A common technique for deceiving human subjects (but not automatic pilots) is to apply only transients to the cockpit and then to decay the attitude slowly to a position such that the local gravity vector is orientated relative to the cockpit in the same way as the computed total acceleration vector. A powerful outside world visual simulation system helps to give a very realistic overall effect.

The magnitudes and periods of linear accelerations which can be produced by any practical rig are quite small. To represent steady excess g the true excess can be applied transiently and then decayed slowly to a low value of deceleration so as to bring the cockpit to rest and finally back to the datum position. Unless this is done smoothly and slowly the pilot will notice the changes in acceleration and in a bad case simply feel the simulated excess g as a momentary jerk.

Simple calculations show that if the deceleration is not to exceed, say, one-fifth of the acceleration and the amplitude of motion is limited to $\pm s$ feet, then the maximum time T for which a particular acceleration, $n \times g$, can be held is given approximately by:

$$T \simeq 0{\cdot}1 \sqrt{\frac{s}{n}} \text{ seconds}$$

If s is ± 6 feet than 1 g excess can be held for 0·25 second, 0·25 g for 0·5 second and 0·1 g for 0·8 second.

These periods are so small that one must consider very carefully whether any attempt to represent sustained linear accelerations is worth while. If not there is no requirement for six degrees of freedom and much of the argument put forward in favour of the platform mechanism described in the paper is redundant.

Although only the largest of three-axis linear-slide systems could give a useful approximation to sustained linear accelerations it is quite possible for the smaller systems, such as discussed here, to represent accurately small-amplitude, high-frequency oscillations. However, such oscillations usually arise from buffeting, touchdown, ground-roll, etc. and are usually associated with a particular direction relative to the cockpit. For this reason they could probably be much more economically reproduced by supporting the cockpit on a short-stroke, two-axis, ram-and-slide system within a three-axis gimbal system.

In the summary the point is made that the platform has

* Voinea, R. P. and Atanasiu, M. C. 'Geometrical theory of screws, and some applications to the theory of mechanisms', *Revue de Mécanique Appliquée* 1962 **7** (No. 4), 845 (in French).

† Manolescu, N. and Manafu, V. 'On the determination of the degree of mobility of mechanisms', *Bull. Polytechnic Institute, Bucharest* 1963 **25** (No. 5), 44 (in French).

no fixed axes relative to the ground and that in some way this makes the simulation of banking easier. This is difficult to understand.

In most aircraft simulators it is necessary to compute the attitude of the aircraft relative to the ground for the following reasons:

(1) To derive the gravity vector components in the conventional aircraft X, Y, Z axes.

(2) To drive artificial horizons, compasses and other instruments.

(3) To drive visual simulation systems.

These outputs are directly applicable to the 'pyramid' or gimbal type of motion system and provided that the servo loops are of high quality the accuracy of simulation of the effects of control depends only upon the accuracy of the computation and is not affected by the type of platform. The platform described in the paper cannot accept the aircraft attitude outputs directly and it is necessary to employ an additional, fairly complicated computer to determine the amount by which each of the rams must extend or contract. Direct attitude feedback from the platform could be a problem and with misalignments a spiral approach to the demanded attitude could occur.

In a gimballed system it is easily arranged that each servo is associated mainly with some of the primary aircraft controls, except for large displacements. One or more gimbals can be locked if necessary and a useful system still results. Differences in the performance of the servos for different axes will not be too disturbing and there is no cross-coupling.

The six-degrees-of-freedom platform must in general operate all six of the rams for any motion. Differences in performance could produce quite noticeable false motions and at high frequencies, where the pilot responds directly to his feelings, a very mistaken impression of the handling of the aircraft could result.

In considering the list of design aims on p. 371 it is suggested that for the purposes of flight simulation the fact that 2–4 were incompatible with 5 should have led to the rejection of 2–4 rather than of 5.

Mr J. Tindale, B.Sc. (*Member*)—As with many other original concepts describing basic principles which before may not have been appreciated in the context, the immediate reaction of the reader is to try to visualize modifications to existing equipment which he senses could be so improved. Then he comes to a grinding halt, because it would seem that any such improvements may be satisfactory from a machine point of view, but to prove their economical viability would require a period of expensive study and development.

Two applications seem to me worth exploring, one is with reference to machine tools, and the other to the seagoing oil drilling rigs, and I commend each idea to their particular industries.

Machine tools design based on simple, co-ordinate geometry for their operational control has of necessity developed along ergonomic lines.

In the modern climate of control technology, this trend may not be justified. The design of a computer controlled machine tool should not be stultified by past concepts of manual control.

Fig. 18 shows an artistic impression of a possible design of a universal mill which could machine complicated shapes with simple cutters. This machine need not be considered specialized although it is conceivable that it could do specialized jobs.

It will be noted that the work is situated low down on the floor and the cutting head is well fixed by sturdy triangulation.

Fig. 19 shows an artistic impression of an oil drilling rig which may suggest an improvement in design over that

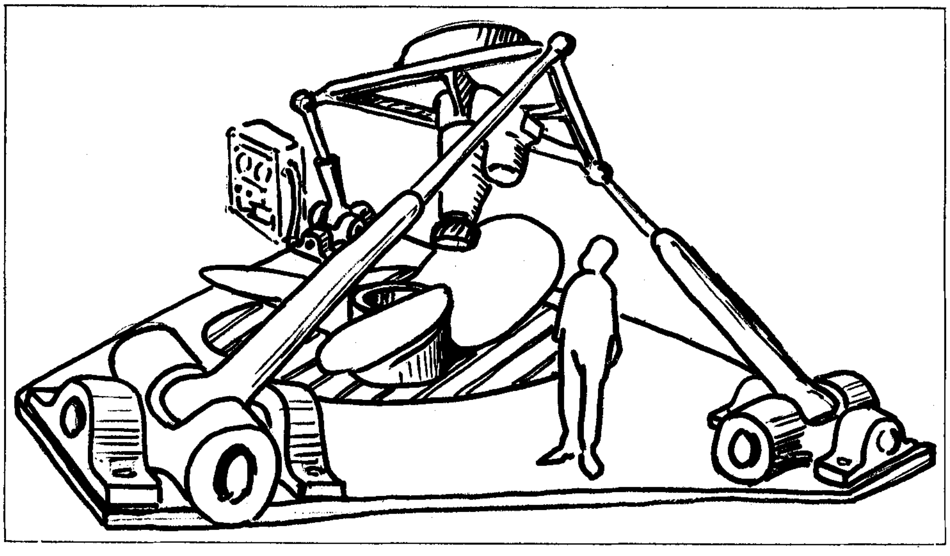

Fig. 18. Impression of possible design of universal mill

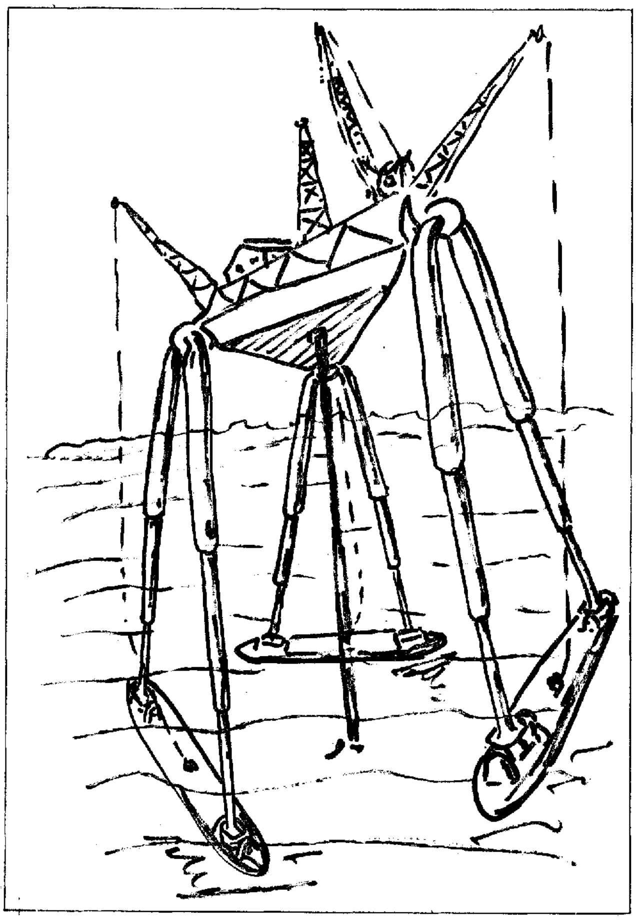

Fig. 19. Impression of possible design for drilling rig

of the ill-fated *Sea Gem.* For stability, the platform is supported on a tripod comprising six telescopic legs, thus there are no redundant members.

For transportation to the site, the six legs forming the tripod would be blown out for buoyancy and would float horizontally on the sea, thus forming a spider-raft. The area covered would give good stability to enable high structures to be built on the main deck, before leaving harbour. On arrival at site, the six legs would have their buoyancy tanks filled and would sink to a vertical position.

The telescopic legs would then be screwed out until they touch the bottom. Any tipping of the main deck, due to the early arrival of one or two of the tripods would automatically be adjusted by reference with a gyroscopically stabilized platform, in conjunction with the telescopic leg controls.

When all three points are in contact with the sea bed, the platform will be raised above the surface still controlled by the stabilizer.

Any settlement after drilling operations have begun would automatically be sensed and corrected.

When the rig has to be removed, the reverse operation is followed, i.e. the telescopic legs are screwed in, strict control being established by reference to the stabilized platform. When the main structure is floating on the sea, the buoyancy tanks in the tripod are blown up, and therefore begin to float up to form the spider-raft configuration.

I hope that these sketch proposals might engender a step into future logical designs based on modern available techniques.

Author's Reply

Mr D. Stewart—I am grateful for the communications on my paper and wish to thank all those who offered comments and criticism.

The replies, I find, fall into three categories which are as follows:

(1) Those that discuss the general engineering values of the mechanism.

(2) Those that discuss the flight simulation problem. These are generally critical of the mechanism for use as a flight simulator.

(3) One from Mr Gough who has brought to my notice an almost identical mechanism which he has designed for use with a tyre testing machine.

In the first category, Mr Tindale has shown a very descriptive sketch of the mechanism used as a universal mill and I am encouraged by his remark that computer-controlled machine tools should not be stifled by past concepts of manual control. It is becoming almost common practice to control conventional machine tools by computers rather than manually, and yet the greater agility of the computer has not been fully realized in the machine tool. I do not know of a universal mill that will permit the cutter angle to be controlled, and yet many components could benefit from such a control. Mr Tindale's suggestions that the mechanism might well be of value in sea-going oil drilling rigs does seem possible, but I sense that there must be many factors governing the design of such immense structures that may preclude its use. My own view is that in such large expensive prospecting machinery the cost of the equipment sometimes unfortunately outweighs the design perfection. Both Mr Murdoch and Mr Meier mention the preferred arrangement that would result from the use of the linear co-ordinate leg system shown in part in Fig. 15 and fully illustrated in Fig. 20. The rigidity of this arrangement is endorsed by the practical application of a similar arrangement described in Mr Gough's communication. I take with interest Mr Meier's suggestion of the use of the mechanism as a stable platform for use on hospital ships.

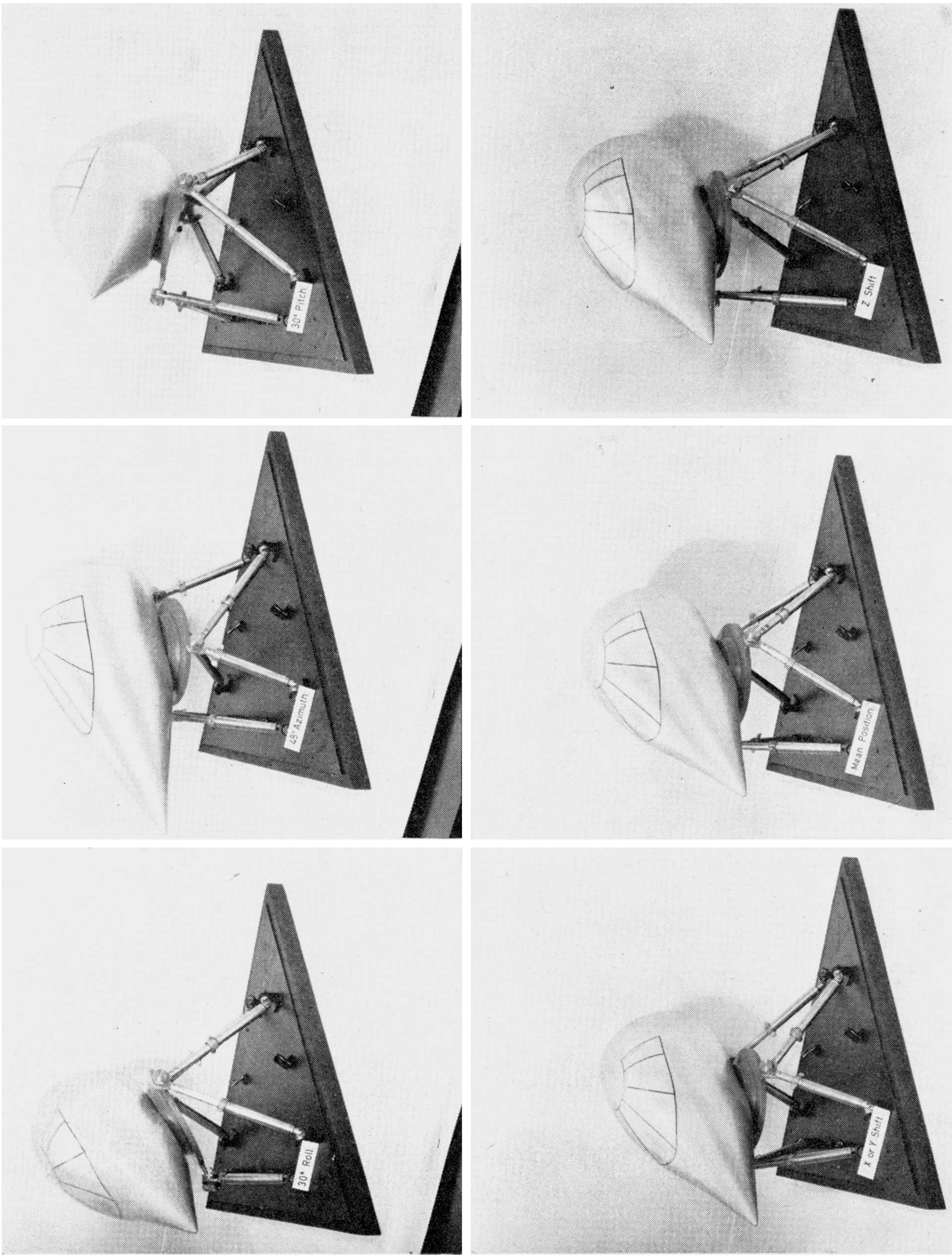

Fig. 20. The use of the linear co-ordinate leg system

Mr Easten mentions that he is considering using a similar mechanism for aiming a radar aerial and since he states the linear motions for this use are not important it does suggest that the structure of the mechanism is simple enough to use even though the full potentials of six degrees of motion are not required. I have built a servo model driven on the lines that Mr Easten mentions and it works quite impressively. I chose to force the driver model by a six-motion joystick and it was found difficult to obtain the same feel in all six motions. The input motions were therefore somewhat jerky. Had I used the principle of putting angular motions in the platform and linear motions in the foundation as suggested by Mr Easten a better demonstration may have resulted. If the motions of jacks are studied in relation to simple platform movements it will be found that over a limited amplitude, and to an approximate value, there are fixed simple relationships between the legs. These relationships can be acquired by simple phase and amplitude monitoring from a single input. I intend to try the control of a model driven from a two-phase sinusoidal input and amplitude divider network and use a six-way switch to obtain the six basic motions.

I am grateful to references given by Mr Hunt and his remarks relating to the pitfalls that exist in special geometrical arrangements. It was only by the use of the constraint criteria that I confirmed the need for a three-axis joint at the platform attachment of the legs, short of making a model. I found it was not possible to prove conclusively when making the design whether three axes were essential or merely safe at the top joint, since I was not intending to rely on rotation between the two halves of the extending leg.

In the second category Mr Thomas puts forward a powerful argument against the use of the mechanism for flight simulation, though most of the points he makes apply to any simulator mechanism that must remain on the ground. Since amplitude in terms of displacement as a result of linear accelerations must always have a limit, the relative merits of one mechanism over another is really a matter of scale. I agree in principle to the inference that for particular flight manoeuvres that do not exercise the full six degrees of freedom a more simple equipment could be designed, and might well have better performance. The mechanism described in my paper is really more suited as a research tool in the study of the general behaviour in flight, since fundamentally it can simulate true flight without any approximations within the amplitude limits set by the scale of the machine. With regards to the question of sustained acceleration such as experienced during turning which is a point also mentioned by Mr Nicholls when he compares the mechanism with a centrifuge, it is possible for the mechanism I describe to exercise a point continuously in a circular path and thereby provide a sustained radial acceleration. If, as in a centrifuge, the acceleration vector is required to remain fixed with respect to the payload it would be necessary to provide a rotating connection between the payload and the platform. Then if the payload is rotated in the reverse direction at the same rate as the orbit of the centre then the equivalent of a centrifuge motion is obtained.

Mr Thomas asks 'are six degrees of freedom really worth while?' As true flight can only be achieved with six degrees of freedom I wonder whether he is not intending to say 'Is simulation really worth while?' I agree that for certain motions it poses very difficult problems but it is surely worth while if knowledge is gained more quickly and without the risk of expensive aeroplanes and human life.

The communication from Mr Gough was read with interest and not without a slight feeling of disappointment in me. Whilst working on my design I was surprised when making searches not to have found the mechanism in use somewhere, since it did appear to be so fundamental; it just shows that I did not search far enough. It is interesting that designs so much alike should result from quite different approach paths. It would appear that whereas Mr Gough derived the six linear jack system directly, the similar arrangement that I describe was as a final variation of a quite different arrangement. The fundamental cube upon which he bases his mechanism did not occur at all in the quite large amount of geometrical calculations that I carried out, and in fact the final geometry does not fit a cube. I would suspect that the relative rigidity of Mr Gough's arrangement and my own is quite marginal but I do think that if amplitude is the main criterion then the geometry as set out in my paper will give higher values size for size. The fact that Mr Gough has been able to have two-axis joints at the top of the legs is due to the freedom of rotation of the screw jacks about their own axis; I did not wish to rely on such rotation since possible linear pick-offs in the legs would have precluded such rotation.

The freedom of rotation of the screw jacks in Mr Gough's mechanism is also the reason why the alignments of the lower universal joints do not comply with my reasoning. I would be interested to know if, when five of the screw jacks are locked, movement of the platform can be obtained by adjustment of the remaining jack. I think not, as movement of the platform will require rotation of all jacks on their own axes.