SOME COMMENTS ON THE DESIGN OF INSTRUMENT DETAILS*

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Introduction

APPLIED photogrammetry is a relatively new branch of technology and there is still a wide field for the inventor in the matter of devising suitable instruments to reduce the cost and improve the precision of the end product, which is usually a map. I assume many of our members have ideas dedicated to that end, and so I feel a few remarks touching the design of instrumental equipment may be of interest, particularly to the younger photogrammetrists.

During the past few years I have seen many examples of scientific instruments and mechanisms designed by young and enthusiastic physicists and engineers, and the observations I propose to make are really a portion of the constructive criticism I have endeavoured to convey to these workers. They are quite elementary, but I feel that some of the simple principles are not always obvious to those concerned. Actually the illustrations I hope to show you are all based on existing practical designs.

Kinematical Considerations

Generally, in instruments and associated light mechanisms the forces are small, and hence questions of stress and strain, which are so prominent in much engineering design, usually assume minor importance. At the same time these small forces, which as a rule, we cannot calculate, often give rise to serious effects, e.g. the deflection of an instrument part due to its own weight may cause intolerable errors, and minute departures from true geometrical form often produce equally objectionable results. To cope with effects of this kind, and to obtain satisfactory performance of moving parts, it is often of great benefit to consider the elementary principles of geometric, or kinematic design.

As a starting point, experience shows us that, in general, we can only make a body contact a surface at three points. Any additional contacts arise from, or produce deformation and are uncertain. Therefore we find that precision instruments are frequently carried on three supports, so that no distortion can be produced from the reactions at the supports. Examples are provided by first order geodetic theodolites, precise levels, spectrometers, cathetometers, etc.

To carry the subject a little farther, we find a body can be completely located with respect to a supporting frame by *six* points of contact, the positions of which must be properly selected. These six points are so chosen that no movement of any kind is possible, and, analogous to the simpler case of the three point support from a surface, a seventh point of contact will, generally, produce deformation of either the body or its support. Actually, closure forces are necessary to maintain contact between the body and its supporting frame, but these are usually gravity or the elastic force of a spring, and can act in such a manner that the resultant passes through a point of contact and so sets up no distortion or couple.

We can obtain a mental picture of what is involved by considering that we have completely fixed a body in position if we prevent motion along three mutually perpendicular axes, and also prevent rotation about each of these axes. If we now remove one of the constraints opposing movement in one of the axial directions, our body is left free to move in this particular direction with the

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other five movements still opposed. This covers the very common case of the sliding member, frequently occurring in mechanisms, and shows that five constraints are necessary and sufficient for such a member. Removal of one more constraint allows, in addition, another movement, linear or rotational, and so on until, when all have been removed, the body is completely free, and is said to have six degrees of freedom.

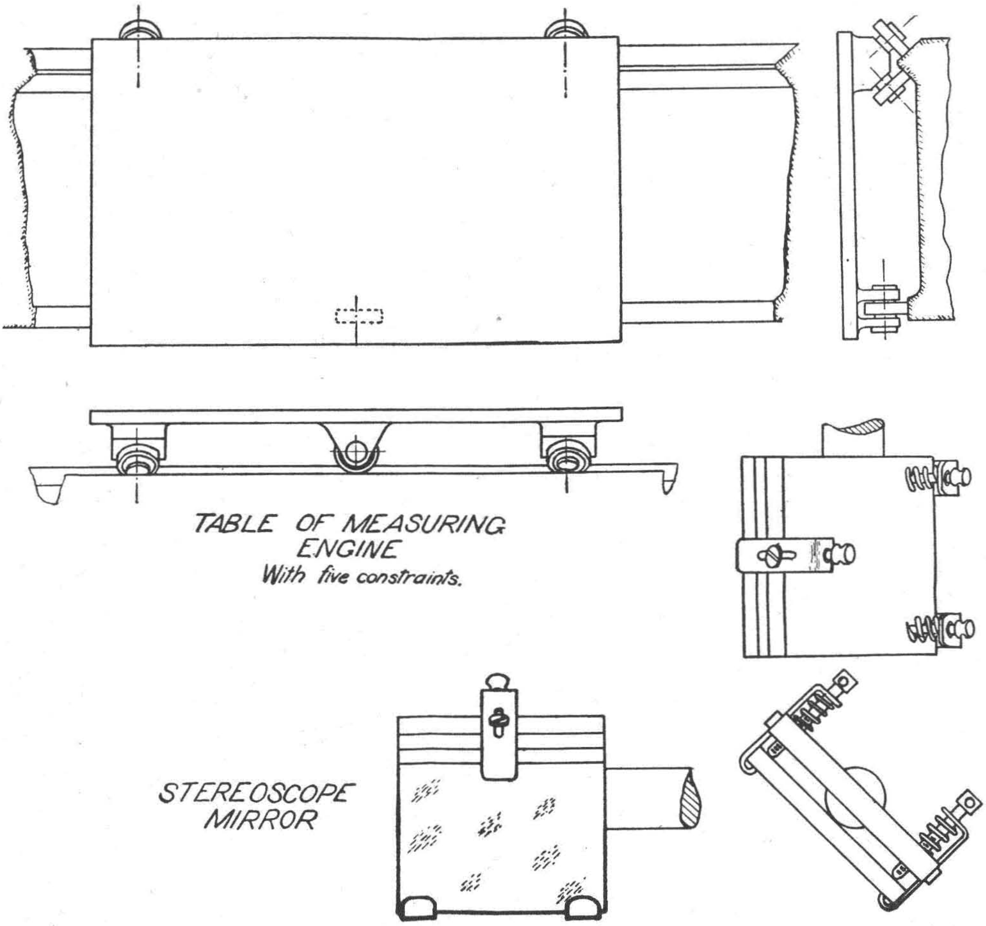

FIG. 1

Now this discussion, so far, has been somewhat theoretical. When we think of a "body" there is in the back of our minds the idea of the rigid body of the mathematician—a mere fiction. In practical mechanisms the parts we have to think of are elastic or even plastic, and so deform under the action of forces. Also, at contacts there must be definite areas involved, rather than points, and, as we all know, an object supported on three legs can, under some circumstances, be extremely unstable. Hence the instrument designer must be prepared to compromise and use judgment in applying kinematic principles to overcome some of his difficulties and thus his occupation becomes something of an art.

EXAMPLES

In the lower part of Fig. 1 there is an example of the use of a three-point support for a surface. This is one of the mirrors of a precision stereoscope, which is held against the ends of three screws, tapped into the supporting bracket. Closure is maintained by three spring-loaded clips, with points of application immediately opposite the screws. This method of support permits adequate adjustment of the mirror, and yet it cannot be distorted.

On the same figure is a good example of a sliding member with five constraints designed by Mr. D. W. Mann of Lincoln, Massachusetts. It is the work carriage of a coordinate comparator, in which the work (for example a photographic plate) is moved in the field of a fixed sighting microscope by means of a micrometer screw. There are two supporting rails on the cast iron bed, one flat and the other vee-shaped. A single ball-bearing roller supports the weight of the carriage at the flat rail, and two pairs of similar rollers engage with the vee rail. Here you see the five necessary and sufficient constraints, leaving the carriage free to move along the guide rail under control of the micrometer screw.

There are other features about Mr. Mann's instrument which are instructive. Notice that guiding is done from one rail, the second, flat, rail merely acting to prevent rotation of the carriage about this guide. It is a common mistake among students and other beginners in designing a slide like this to make the carriage fit two parallel vee-rails. This entails difficult and costly fitting in the shop, and even then the action of the slide will not be so satisfactory as with a single vee slide. Other examples of needless fitting can often be found in instrument parts, and it is always a good precept to examine the design of an instrument carefully, with a view to removing all contacts between different members which are not essential to the correct functions of the instrument.

The screw and nut pair are a good example. We find it in nearly every measuring instrument—very often it is the most important part. Now it is particularly difficult to make a straight screw, and even more so if the screw is long, and hence we have to take special pains to ensure that moving nuts are as free as possible from constraint, quite apart from considerations of kinematic design. There are various ways of doing this, in Mr. Mann's comparator for instance, a buttress on the nut contacts a buttress on the sliding table and so governs its movement.

In Fig. 2, another example of a screw-operated slider is shown. This is part of a mechanism recently designed with the knowledge that it would be built by instrument-maker trainees, having limited manual experience. It is operated by a long, rather thin screw, and in this case the guides are turned bars. The slider consists of a stiff webbed bracket, which carries two short bronze bushings, bored to fit the first guide rod. A third narrow bushing is scraped to fit the second guide rod at the top and bottom, but is relieved at the sides. Here we have the slider constrained so that it can move freely along the guides, even if these are not perfectly straight and parallel. On the other hand there is no shake or allowable motion about the guiding slide. The nut is made a good fit at its end between the flat surfaces of two lugs, but it is free to move about if the screw has long radius bends. It is held against rotation by machining in it a longitudinal slot which fits a pin joining the two plates. The screw of this slide works quite freely without lost motion—and yet there is no binding tendency.

This freedom of the nut can be carried still farther. For extreme precision the nut may be connected to the member being moved by a simple ball-ended strut. We have again removed all unnecessary constraints. All our nut has to do is to push the member along a slide of some sort, and there merely remains the need to prevent rotation of the nut and maintain its contact with the member. The first is easily done by fitting a tail to the nut and letting the tail end fit in a slot. This slot may be shaped to eliminate calibration errors in the screw, and is

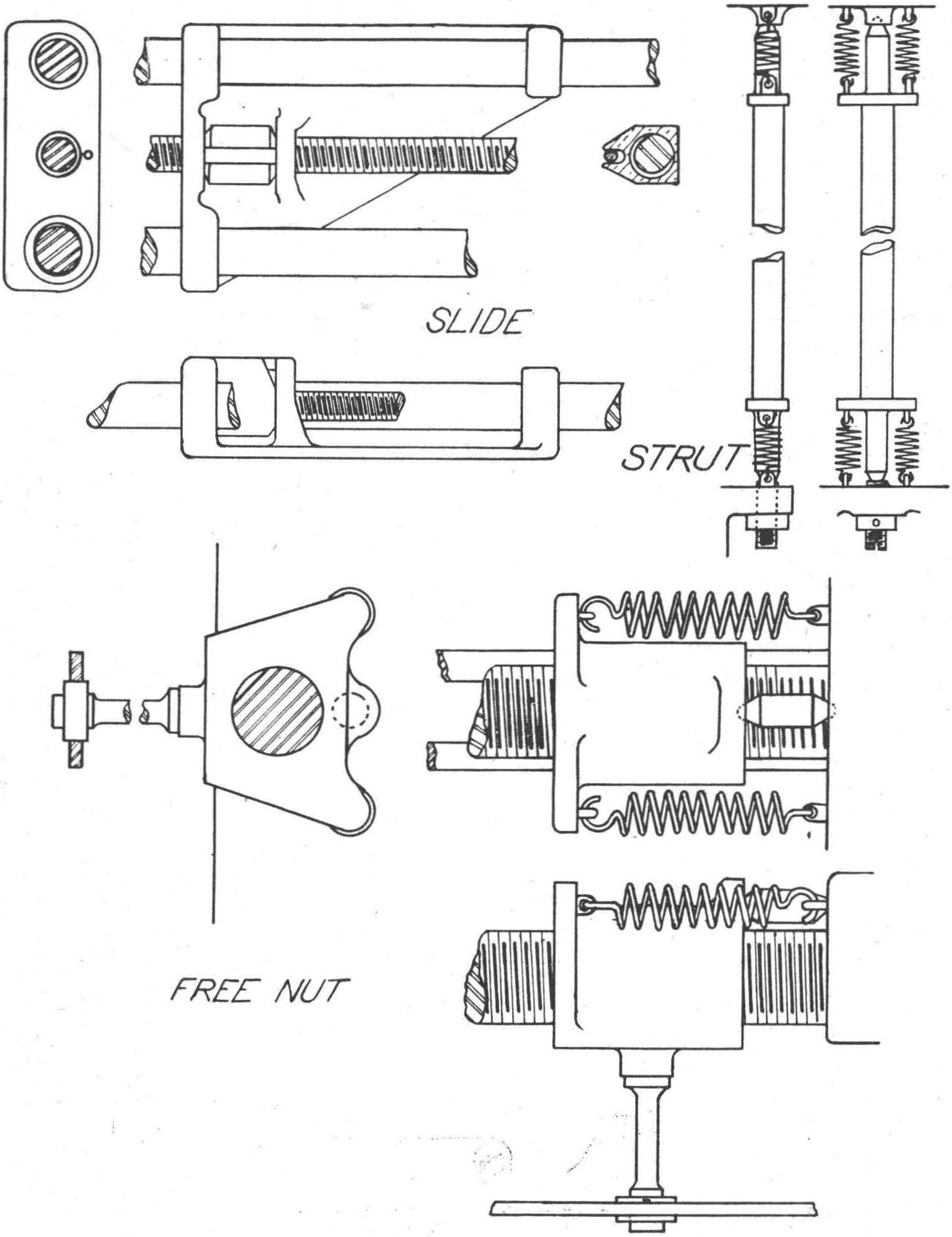

FIG. 2

so utilized in Mr. Mann's comparator and in precision dividing engines. Closure is easily maintained with the aid of springs or by a weight, cord and pulley, according to the characteristics of the machine in question. This free nut is sketched in Fig. 2.

Struts with spring closure are very useful when it is necessary to operate one sliding member from another without transmitting undesirable shear forces.

They also are easily made adjustable in length, and so facilitate fitting and calibration. The strut coupling in Fig. 2 was used in a compound stereoscope, and is about 16 inches long. The central part is a thin-walled tube, fitted with flanges to anchor the closure springs. The ends are of steel, made a push fit in the tube. One of the buttress fittings has a screw, with the end cupped to fit the strut, and

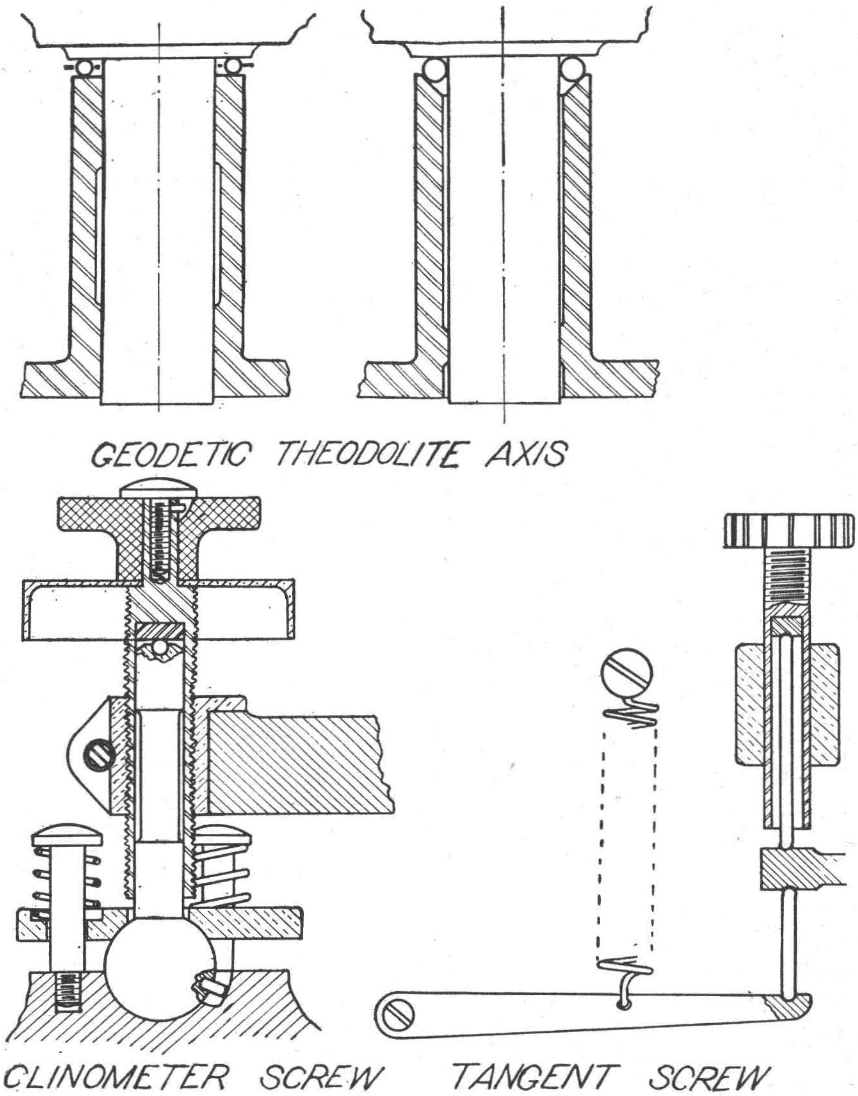

FIG. 3

is equipped with a locknut, which is tightened after adjustment. Incidentally the use of struts like this brings home to young instrument-designers the need for applying a force in an instrument as nearly as possible along the line of the reaction, and so avoiding undesirable couples, and consequent distortions or errors.

In Fig. 3, at the right, is shown the application of struts to slow motion, or tangent, screws. With the usual design, where the end of the screw is in direct contact with the moving part, it is quite common to find irregularities in the motion due to the slipping action at the point of contact, particularly when the direction of movement of the buttress is not collinear with the screw axis. By using struts in the manner shown, a much smoother action will be obtained, and there is no tendency to move the buttress in a direction perpendicular to that of the desired motion.

The end thrust bearings for screws used in measurement must be carefully designed and fitted. Unless great care is exercised a periodic axial displacement

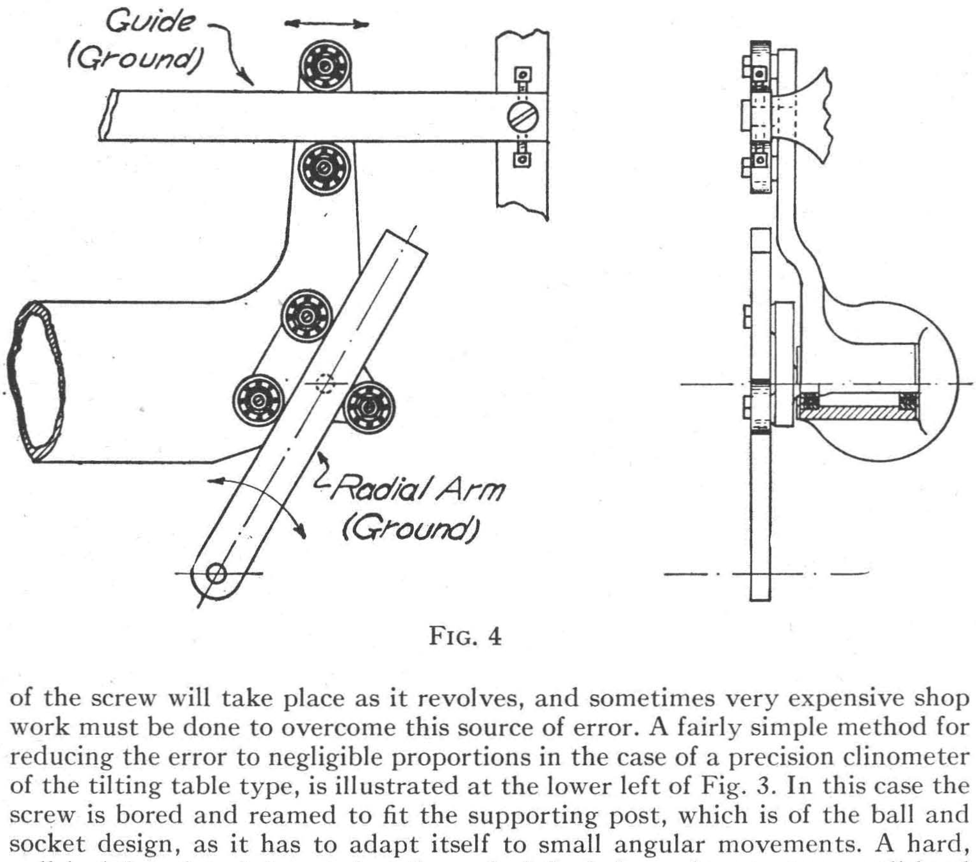

FIG. 4

of the screw will take place as it revolves, and sometimes very expensive shop work must be done to overcome this source of error. A fairly simple method for reducing the error to negligible proportions in the case of a precision clinometer of the tilting table type, is illustrated at the lower left of Fig. 3. In this case the screw is bored and reamed to fit the supporting post, which is of the ball and socket design, as it has to adapt itself to small angular movements. A hard, polished flat plate is inserted at the end of the hole, and contacts a small hard steel ball inserted into the exact center of the post.

FRICTION

Friction is undesirable in most instruments. By giving consideration to kinematic principles, unnecessarily large surfaces of contact can be avoided. Long sleeves on cylindrical bars should be relieved at the center, leaving two narrow-bands fitting at the ends—with consequent allowance for adaptability to inevitable small departures from straightness in the bar. In some investigations made a few years ago at Ottawa by the Geodetic Survey of Canada, it was found that the hardened and ground cylindrical pivot of a precision theodolite working in a cylindrical socket gave trouble due to extremely slight departure of these members from their geometrical form. Although the "feel" was satisfactory, the force produced when the pivot rotated in its socket was enough to distort the telescope of the theodolite with respect to the horizontal circle in the base. The angular error was only a second or so arc, but it was definitely there. In Fig. 3 a diagram is shown illustrating this pivot, and its modified form, when the error disappeared.

Friction at sliding contacts can often be reduced by using as rollers journal type ball bearings working on flat cold rolled steel or cast iron surfaces. Such rollers are very useful in linkages of the type often found in mechanical plotting machines and similar mechanisms. By mounting the rollers on eccentric pins, i.e. such that the portion of the pin on which the roller is mounted is eccentric to the portion fitting in the support, lost motion can be readily taken up without imposing any exacting requirements on the mechanic. Moreover, the eccentricity can be utilized in adjusting the instrument parts until they conform to the geometrical relationship in the linkage which is often essential for correct performance.

The use of this type of coupling is illustrated in Fig. 4, which shows, diagramatically, part of a plotting machine based on the radial line principle.

In Fig. 4 the rotating arm reproduces the radial direction on a vertical air photograph. As it revolves it must move another member in the direction of the air base, as materialized by the guide. To couple the radial arm to the moving member a pivot is mounted in two ball bearings and is fitted at its outer end with a triangular plate on which are mounted three bearings, engaging with the arm as shown. For correct performance it is necessary that the axis of the arm intersect the axis of the pivot, and this is easily accomplished, during the calibration of the machine, by adjusting the eccentric pins on which the three bearings are mounted. The coupling to the air base buide is very similar, and can be adjusted in the same manner.

Couplings of this type will work satisfactorily at angular relations of the mechanism where sliding contacts would jam due to the frictional effect. Yet, at the same time, lost motion can be virtually eliminated.

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