TECHNICAL REPORT

Optical Tooling Applications

Part 1

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Editor's Note: The following thesis was prepared for the Dept. of Civil Technology, Ryerson Polytechnical Institute for the partial fulfillment of the requirements for the Bachelor of Technology Degree in Survey Engineering. It was awarded the A.O.L.S. First Prize for 1982 for such material prepared at Ryerson.

Optical tooling has become an important field in surveying in recent years due to the increased demand for producing manufactured products to greater accuracies, for the precise alignment of large rollers in factory mills, etc. etc., and is a field that appears to have been largely overlooked by members of this Association.

The paper is presented in two parts. Part 2 will appear in the next issue of the Quarterly.

T.P.J.

ABSTRACT

THE PURPOSE of this investigation was to carry out an experiment to determine if there was any wobble in the axis of the shop lathe, by using autocollimation procedures. An explanation of autocollimation and several other important procedures used in optical tooling were also presented in this thesis. These topics provide the theoretical background knowledge which is necessary for the comprehension of the methods utilized in the lab experiment.

The results of the lab showed that there was a definite wobble in the lathe axis, although the amount could not be determined numerically. The wobble was symmetrical about the rotational axis, as indicated by the final plot.

It was also found that the resultant mirror inclination (total mirror misorientation), must be known before the wobble of the axis can be determined.

INTRODUCTION

Optical tooling became widely accepted in industry after World War II because of the necessity to build large numbers of planes and ships. In the past few years, it has become even more important because of the demand to build components to greater accuracies. The optical principles involved provide the needed accuracy, and as of yet, no other system is capable of obtaining better results.

The purpose of this thesis is to utilize the optical tooling principles, mainly autocollimation, in an attempt to assess the rotational accuracy of the shop lathe. The major principles and procedures in optical tooling, most of which are relevant to the lab project, will be discussed first.

The beginning part of this thesis, deals with tolerances and errors and their significance in optical tooling. The next major section discusses a few important optical principles and the various optical tooling procedures, along with several applications. Emphasis has been placed on the autocollimation procedure. The final section is devoted to the lab project which is performed by using autocollimation procedures.

GENERAL

Optical tooling is a branch of surveying where the primary function is to establish and control the size and alignment of structures and manufactured products to high accuracies and small tolerances. This is achieved by utilizing very precise instruments which are similar to precise surveying instruments, but are capable of performing many operations which surveying instruments cannot perform. This report will not discuss in any detail the types and uses of instrumentation because it is assumed that the reader has an understanding of the basic optical tooling instruments used in industry. The report will, however mention a few of the newer instruments, which have recently appeared on the market, and which are best suited for performing certain operations.

It must be pointed out that optical tooling also provides an alternative means of solving existing measurement problems, which are very difficult or impossible to solve by other conventional methods.

The procedure to adopt in the solution of any particular problem, must be decided on the basis of the degree of accuracy required. The accuracy attained will then depend on how well the procedure is implemented (this requires a comprehensive knowledge of optics), the instrumentation used, and the geometry of the instruments involved.

TOLERANCES AND ERRORS

In optical tooling, the aspect of tolerances associated with measurements becomes very important, in fact more important than in surveying because of the higher accuracies that must be obtained. "In general, the accuracy that can be attained is 1 part in 200,000." This means that for a point distant 2 metres for example, the distance and alignment can be located within a tolerance of + — 0.01mm., as shown below.

At 2 metres: $\frac{2{,}000\text{mm}}{200{,}000} = \frac{1}{100} = 0.01\text{mm}$

The same procedure can be used to compute the allowable tolerance at any distance. For example, at 30 metres (approximately 100 feet), the tolerance would be

$$\frac{30{,}000\text{mm}}{200{,}000} = \frac{1}{6.667} = + \text{—}\ 0.15\text{mm}$$

To obtain this accuracy (1: 200,000) for the direction of a line, the line must be correct to one second of arc, as shown in Diagram No. 1 for the case of a thirty metre line.

The reason for such high accuracies and tolerances is due to the fact that modern industry operates on the basis of interchangeable manufacturing. This means that parts must be manufactured to such a degree of accuracy as is necessary to permit the proper functioning and assembly of the parts without additional machining required, even though the individual parts may have been made in different places and at different times.

In actual practice however, it is not possible to make parts and products that are perfectly interchangeable because many errors still exist. Not only do machines have inherent inaccuracies built into them, but every measurement or machine setting made by a human is also subject to slight inaccuracy. All optical tooling instruments have manufacturing tolerances associated with them, which affect their accuracy. These tolerances are fairly small and can usually be neglected or eliminated by some procedure, i.e. (double centring in the case of a theodolite). In any case, the instrumental tolerance must be related to the accuracy required in the work for which it is utilized, because if it isn't, a more appropriate instrument should be chosen to do the job. For example, a tolerance of 0.01mm in a measurement made at 30 metres is negligible if the tolerance required at this distance is 0.05mm However in some cases, tolerances may be additive, and can also be magnified to an unacceptable value by improper procedures. It is important that the effect of all likely errors be assessed in the planning stages of the job, and to give careful consideration as to the procedures to adopt, in order to minimize the errors. "Even if the errors cannot be avoided, it may be sufficient to know the approximate magnitude of any error so that the precision of the result can be estimated."

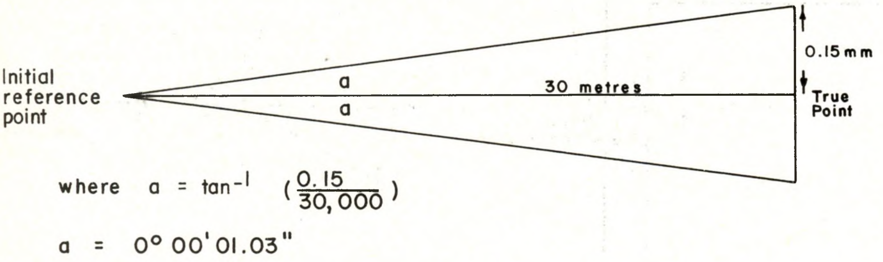


Diagram 1

Baselines should be established with the greatest possible accuracy because all subsequent measurements are taken from this line. To do this effectively, the baseline should be as long as possible. Any intermediate points would then contain proportionally less error than in the total baseline. If on the other hand, a short baseline is used for making measurements on targets which are further away from the instrument than the target which was used to establish the baseline, the errors and tolerances in these pointings will increase proportionally with distance. Therefore short baselines should be avoided.

CORRECTIONS

In optical alignment and vertical angle measurement, the effects of earth curvature, and curvature of the light ray due to atmospheric refraction may not be negligible. Even though these effects are generally thought to be applicable only over long lines, they may become significant in optical tooling where relatively short lines are used, depending on the required accuracies. See Table 1.

Temperature gradients in the atmosphere caused by differential heating and cooling of air layers, can cause refraction or bending of the light ray. Currents of air of varying temperatures crossing the line of sight will cause the image to shimmer, making it difficult to obtain an accurate measurement. The index of refraction of air generally fluctuates in a random manner because of air turbulence and temperature changes. To reduce the effects of refraction and shimmer, fans should be directed away from the line of sight if possible. In certain cases the line of sight may be protected by passing it through a tube. In severe conditions where a line of sight of considerable length passes near boilers or furnaces, it may be necessary to enclose the line of sight in an evacuated tube.

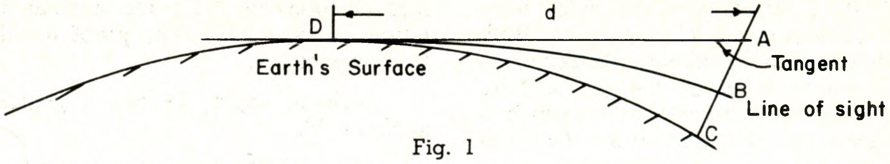


Fig. 1

DC is a level surface which is perpendicular to the line of gravity.

DB is a line of sight through air which has a constant vertical temperature gradient.

DA is a line of sight through air of constant density or in a vacuum.

AC is the deviation of a level surface from the truly straight tangent to the earth's surface. This can be regarded as accurate.

AB is the amount of refraction of a line of sight from the tangent. This value varies with the atmospheric conditions and therefore only mean values are given.

BC is the combined effect of refraction and curvature of earth. Subject to variation and only mean values are given.

Distance 'd' in metres	AC in mm.	AB in mm.	BC in mm.
2.5	0.00056	0.000075	0.00049
5	0.0023	0.0003	0.002
10	0.009	0.0012	0.0078
25	0.056	0.0074	0.049
50	0.23	0.03	0.2
75	0.51	0.067	0.44
100	0.9	0.12	0.78

Table 1. Corrections for Curvature of Earth and Atmospheric Refraction in mm. (Source: Dagnall)

In Table 1. the corrections (BC) are of most significance and importance. Depending on the allowable tolerances, this value can either be neglected or applied as a correction where necessary.

Local temperature variations are another source of error encountered in optical tooling which must be accounted for. False datums or baselines may result if precautions are not taken to prevent relative movement between the measuring instrument and the work being checked. This relative movement is usually caused by structural movement of one part of a jig relative to another. An example of this is shown in Figure 2 where a temperature gradient of 10°F exists from the floor to the top of the jig. A temperature difference of this magnitude is not uncommon in plants with concrete floors and overhead heaters. In this example, both the top and bottom members of the jig are 20 feet in length when at the same temperature. Due to the temperature difference, the top member has expanded by 0.015 inch to 20.00125 feet, and the sides have gone 20 seconds out of parallel. With a telescope and collimator attached to the opposite sides of the jig, a false datum line has been established which is displaced by 0.03 inch from the original jib datum.

It can be seen that errors of this type are not always negligible, in fact they could cause large errors in setting up. This points out the importance of making frequent checks back to a datum target. These errors of course are a function of the thermal coefficient of expansion of the material from which the jig is made. An inch length of the average ferrous material will alter by 0.000006 (6 millionths) inch with each Fahrenheit degree change in temperature. A similar figure for aluminum is 13 millionths and copper 9 millionths.”

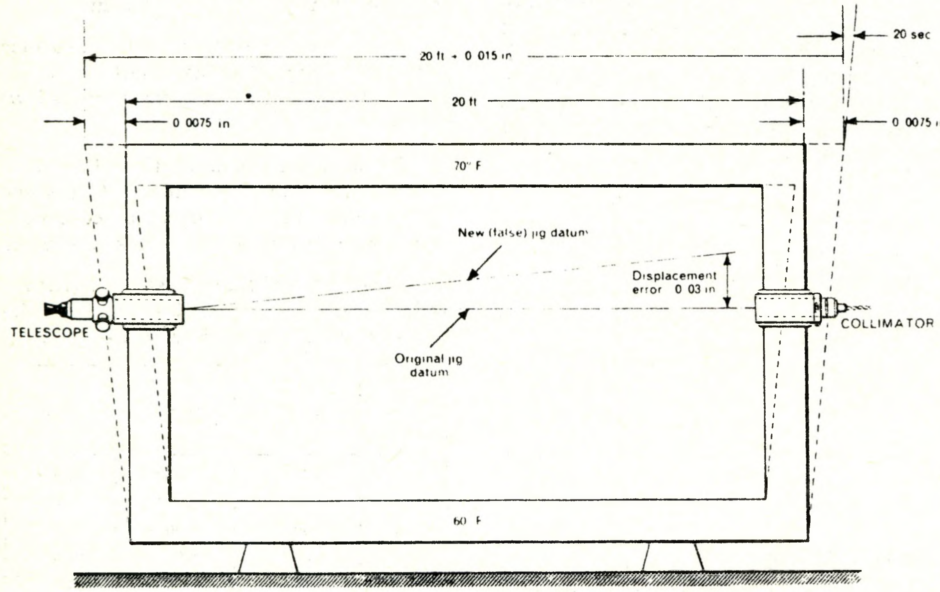


Fig. 2

Therefore the structural stability of a jig depends on the material from which it is made.

PROCEDURES AND APPLICATIONS

Before the various optical procedures are discussed, it is important to mention a few basic optical principles which are common to both autoreflection and autocollimation.

When dealing with plane reflecting surfaces (such as autocollimation and autoreflection mirrors), the angle of incidence is equal to the angle of reflection when a light ray is reflected from the surface. Angle ‘b’ is referred to as a glancing angle. (Diagram 2)

When the reflecting surface is rotated from the incident ray, and the incident ray is held constant, each angle is changed by the amount of rotation. The reflected ray deviates from its original position by twice the angular rotation of the mirror. The proof for this is shown below;

Incident angle RS has a glancing angle of ‘b’.

Mirror M^1N^1 is rotated through an angle ‘d’ to M^2N^2.

When the glancing angle is ‘b’, the deviation angle ‘TSR’ is 2b.

After rotation, the glancing angle is (b + a) and therefore the deviation angle is 2(b + a).

Therefore the reflected ray is rotated by

$$c = 2(b + a) - 2b = 2a$$

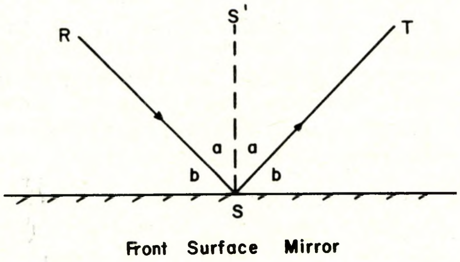


Diagram 2

AUTOREFLECTION

Autoreflection provides a method of establishing perpendicularity, and measuring small angles of tilt, fairly accurately. By using optics, absolute right angles can be established. This method does not achieve the same accuracy as autocollimation which will be described later, but it gives greater clarity of results when the object is greater than 50 feet from the checking instrument. The reason for this is that the autoreflection target, which fits either directly onto the objective end of the telescope or on the inside surface of the objective, has a distinct outline whose reflection is clearly seen, even at long distances. The centre of the target should intersect with the principal point of the objective lens (the line of sight) to give accurate results. Since this condition is not always satisfied, the method lacks the accuracy associated with autocollimation. Possible inaccuracies could also exist between the optical axis and the mechanical axis of the telescope.

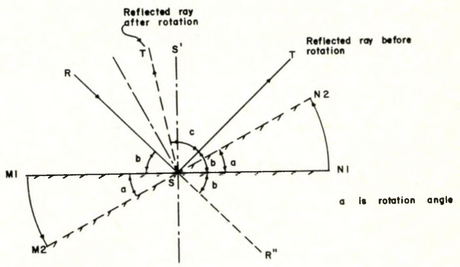


Diagram 3

When an object is to be positioned using autoreflection, an optically flat target mirror is mounted on the part to be positioned in such a way that its reflecting surface is parallel to the reference plane on the part, and so that it will be in the line of sight of the alignment telescope. In order that the autoreflection target is visible, it must be illuminated from behind. The telescope must be focused to twice the distance between the mirror and the objective lens of the telescope, in order to get a reflection from the mirror. If a reflection is obtained, the part can be tilted and turned in an appropriate manner until the crosshairs of the telescope become superimposed with the image of the target mounted on the end of the telescope. The part will then be positioned perpendicular to the axis of the telescope.

When parts have to be positioned at certain offsets from a line of sight, optical planes which are perpendicular to the line of sight can be established at the required stations. This can be accomplished by autoreflection with a jig transit or by using a pentaprism attachment on the theodolite.

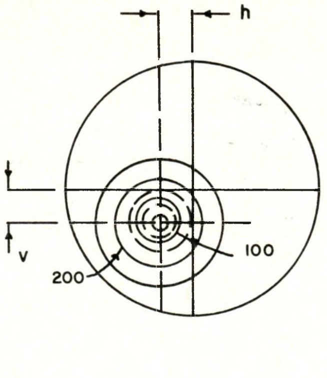
The same type of mirror targets are used for both autoreflection and autocollimation and will therefore be discussed in further detail in the autocollimation section.

One application that will be considered here is the method of checking parallelism and alignment of a shaft by autoreflection, using an alignment telescope. The same basic application is considered in the lab project except that it is done by autocollimation. Therefore, the procedure by autoreflection will be included to give a general comparison between the two methods. This procedure assumes that there is no wobble in the axis of the shaft.

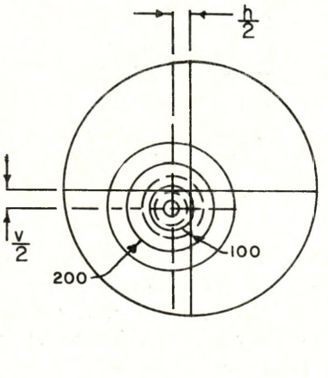
Procedure: This operation allows a line of sight to be established along the shaft axis as a datum line. This is useful in such operations as checking the alignment of a bore. The telescope is set up in a position facing the end of the shaft. A mirror target is mounted on the end of the shaft in such a way that it is concentric with the axis of rotation. This can be accomplished using a locating shoulder. The telescope is focused to twice the distance between the telescope and mirror, and the target illumination is turned on. The micrometers are set to zero. By using the adjusting screws on the telescope bracket, the image of the cover glass target is centred on the crosshairs. This makes the line of sight perpendicular to the mirror although the mirror may not yet be perpendicular to the axis of rotation. The axis is rotated through 180°. If the mirror is not perpendicular to the axis of rotation, the image of the target will move away from the crosshairs by the amounts 'h' and 'v' as shown in Figure 3(a).

Without further rotating the axis, the telescope is adjusted to eliminate half of the error in each direction. (Fig. 3(b)) The mirror is now adjusted to eliminate the other half of the error. (Fig. 3(c)) The previous three steps are repeated again until all the error is gone and the target image remains centred on the crosshairs as the shaft is rotated. The line of sight is now parallel to the axis of rotation but not necessarily coincident. The target illumination is turned off and the telescope is focused onto the mirror target. If the image is displaced from the crosshairs, it means that the line of sight is not coincident with the shaft axis.

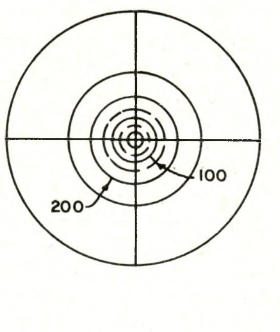
This offset can be measured by using the horizontal and vertical micrometers. The telescope can now be displaced by the amount of the offsets to bring the line of sight in line with the axis.



(a)



(b)



(c)

AUTOCOLLIMATION

The principle of collimation will be outlined first, since the operation of any autocollimating instrument is based on this principle.

The term collimate means to produce parallel rays. This is accomplished in an instrument where a source of light is situated at the principle focus of a converging lens. Light rays emanating from any point in the focal plane of the lens will emerge from the lens as beams parallel to the principle axis. In optical tooling this principle is utilized whenever the lines of sight of two instruments are brought parallel. When collimated light rays from a collimator are viewed with a second instrument (a telescope) focused at infinity, an image of the illuminated crosshairs of the first instrument (collimator) appears on the reticle. If the line of sight of the collimator is parallel to the line of sight of the telescope, the crosshair image of the collimator will coincide with the telescope crosshairs, irrespective of whether there is a displacement between the two lines of sight.

If the axis of the collimator is tilted with respect to the telescope axis, the crosshair image will appear off-centre. In this case, the collimator could be used as a device for determining and measuring tilt with respect to the telescope axis.

Since parallel rays are involved in collimation, the distance between the two instruments is of no importance, ie. one could be directly in front of the other. Therefore collimators are very useful in establishing reference lines for angle measurement, when sighting distances are limited. They can also be used as references against which levels and theodolites can be checked and adjusted.

In autocollimation, the same rules apply which have just been described in the procedure which utilized a collimator and a telescope. The only difference is that there is only one telescope used, since the other can be referred to as the mirror image of the actual telescope.

The process of autocollimation is using a telescope focused at infinity, and sighting an optically flat mirror. The reticle which lies in the focal plane of the lens must be illuminated from the eyepiece side. This results in the rays of light leaving the objective lens as parallel beams, as mentioned previously. If these parallel light rays are directed at a mirror, an image of the crosshairs will be seen somewhere in the focal plane. If the mirror is exactly perpendicular to the line of sight, the light rays will be reflected back along their original paths, forming an image of the crosshairs exactly on the actual crosshairs themselves. Autocollimation is obtained when this occurs.

As was mentioned earlier, autocollimation is not possible unless the telescope is focused at infinity. When a mirror is placed outside of the shortest focusing distance of the instrument, an image of the crosshairs can be formed by focusing to the mirror, however this image cannot be used for autocollimation. "It can be easily distinguished from the autocollimation image by the fact that it does not move in relation to the telescope crosshairs as the theodolite or mirror is turned."

When a reflected image is obtained from a mirror surface, the reflected crosshairs will be of the same thickness as the actual crosshairs because the magnification is 1:1. This condition holds true for any distance of separation between the mirror and the telescope. This consistency of image size is important in maintaining pointing accuracy. When the mirror is positioned close to the objective lens, a return image of the complete reticle is seen. "However, as the distance between the mirror and the objective increases, the size of the image — or, perhaps more correctly, the portion of the reticle of which the image is formed — decreases. The diameter 's' of the image in seconds of arc is approximately

$$s'' = \frac{d}{2D \sin 1''}$$

where d = diameter of telescope objective

D = distance between instrument and mirror

If a T2 theodolite with a 40mm objective is 50 metres from the mirror, the diameter of the image will be about 80" seconds. If one considers that the double vertical hair of the T2 reticle subtends about 40", it will be realized that the image at 50m is small, although autocollimation measurements can still be made comfortably." Autocollimation can easily be done at a distance of "50m or more from the mirror and the distance has sometimes been up to 100m" Seldom does any machine part in industry have to be positioned at a greater distance than 100m, and if such a case exists, it can be done by alternative procedures.

Up to now, only the case of exact perpendicularity between telescope and mirror has been considered. If the mirror is now tilted through an angle 's', the reflected ray will deviate by '2s' (Refer to optical principles mentioned earlier). An image will be created in the same perpendicular plane as the light source (focal plane) provided the mirror hasn't been tilted too far to prevent the reflected rays from entering the telescope objective. The resulting image will be displaced with respect to the telescope crosshairs and will be inverted. (Figure 4a and b)

In Figure 4 the reflected crosshairs are inverted because "the reflected erect virtual image is inverted when imaged by the lens. Both real and reflected crosshairs will be again inverted by an erecting eyepiece."

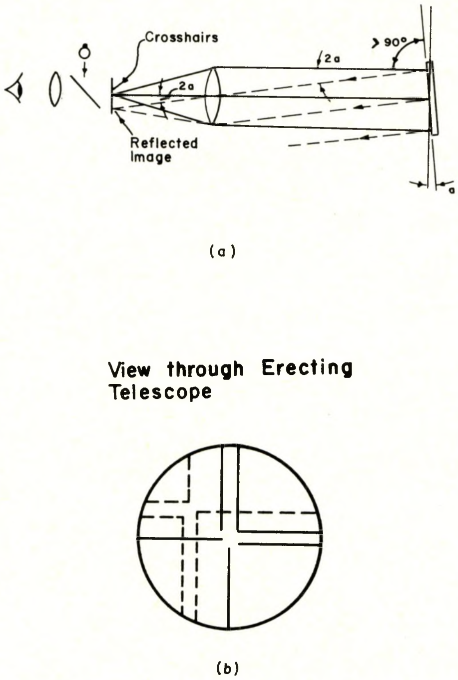


Fig. 4 Autocollimation
a. Mirror is tilted by 'a'. Reflected rays are moved through '2a'. Crosshairs and image no longer coincide.
b. In (a) the image appears below the crosshairs, and in (b) when viewed through the eyepiece, the reflected crosshairs being inverted are now above the actual crosshairs.

The position of the reflected image in the focal plane is not dependent on the distance of the mirror from the objective. In other words, if the mirror is moved gradually away from the telescope, and maintaining its original tilt, all the reflected images will fall at the same point. In summary it can be stated that "when the beam is parallel and passes through the lens, the position of the image depends only on the direction or angle of the parallel beam relative to the instrument's optical axis, and not the position at which the reflected beam strikes the lens."

One of the most important uses of autocollimation is for measuring angular tilts (i.e. tilts of the mirror when it is positioned on a machine part). This technique forms the basis for the lab project.

The theodolite is pointed at the mirror, and by using both horizontal and vertical tangent screws, the reflected image is made to coincide with the crosshairs. Both horizontal and vertical circles are read (Hz1 and V1). The mirror or the item fitted with the mirror is now tilted or turned into its second position. To measure the angles through which the mirror moved, the crosshairs and their image are again brought in to coincidence by autocollimation, and the circles are read again (Hz2 and V2) The amounts by which the mirror was turned in the horizontal and vertical is $\triangle$Hz and $\triangle$V respectively where $\triangle Hz = Hz1 - Hz2$ and $\triangle V = V1 - V2$

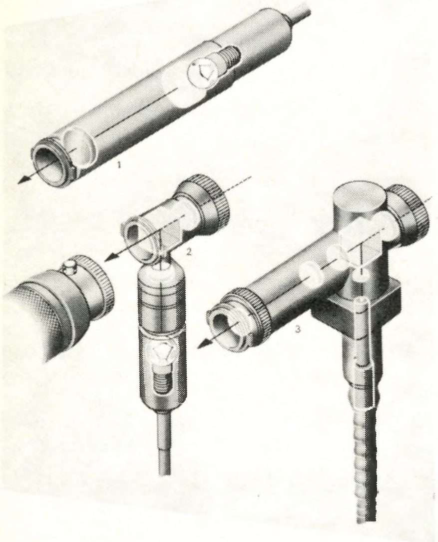
Even though it is not the intent of this report to deal specifically with lasers in optical tooling, it must be stressed that these principles which have been discussed, apply to lasers as well. Autocollimating lasers use the conventional target mirrors. The only difference in this system is that a centring detector built into the laser head, gives an indication of the relative angular position of the mirror with respect to the laser beam. In other words if the mirror is exactly perpendicular to the beam, the centring detector will indicate a null. If the mirror is tilted with respect to the beam, the angular displacement in the two axis can be read from the two meters.

ADVANTAGES

Autocollimation provides the most accurate means of determining perpendicularity. In autoreflection, there is always the possibility of the cover glass target not being exactly centred and therefore a slight error may be introduced.

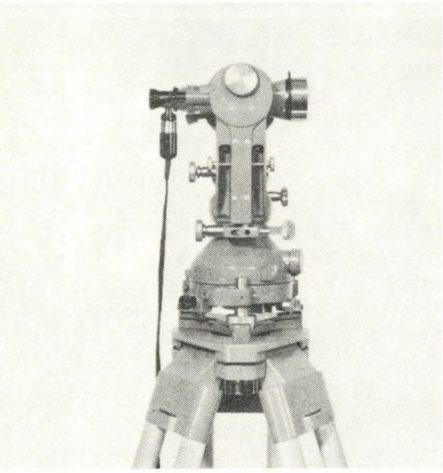
Since this target is not used in autocollimation, no error is involved and therefore this method provides greater accuracy especially for very short distances. Also in autoreflection an error may be introduced if there exists a curvature in the line of sight as a result of having to focus at different distances. In autocollimation, this error does not exist because the telescope is always kept at infinity focus. With the focus set at infinity, there is no minimum distance for autocollimation. Pointing errors at infinity are virtually nonexistent and this is why autocollimation is used so extensively in industry. When using autocollimation for precise angle measurement, exact centering of the theodolite over a point is not necessary. The same applies to pointing on the mirror. It is not important where the line of sight intersects the mirror, except that if the mirror protrudes only partially into the bundle of rays, the reflected image will be weaker. The angular relationship between two mirrors does not change by autocollimating to two different points on the mirror. The accuracy of pointing with an autocollimator as opposed to a collimator is increased two times by the fact that a reflected ray from a mirror is deflected through 2a for an angular tilt 'a' of the mirror. Since there are virtually no errors associated with pointing, the accuracy of an angle measurement is dependent solely on the operator's ability to set the micrometer and on the accuracy of the circle and micrometer graduations. "With a Wild T2 theodolite, a good observer will certainly measure to about + 1″; with a Wild T3 theodolite, to about + 0.5″."

AUTOCOLLIMATION INSTRUMENTS



For interchange with telescope eyepiece. 1. Eyepiece lamp. 2. Autocollimator eyepiece. 3. Laser eyepiece.

Some manufacturers have produced special instruments just for the purpose of autocollimation. It is usually more desirable however to have a standard theodolite equipped with an autocollimation attachment unless autocollimation measurements are made frequently. The necessary attachment interchanges with the standard telescope eyepiece and consists of a lamp, beam splitter and a reticle plate at the focal plane. Special diagonal autocollimation eyepieces are also available for tasks where autocollimation measurements have to be made with steep lines of sight. Automatic plumbing instruments such as the Wild ZL and NL when fitted with autocollimation eyepieces can be used to position a mirror horizontally. Levels such as the Wild N3 and NA2 can also be used for autocollimation procedures.



Wild T2 with Autocollimator Eyepiece G0A2.

The use of an autocollimation theodolite is superior to using an alignment telescope because the telescope can only be used for alignment in one direction at a time, while a theodolite can be used for alignment of any point in the horizontal or vertical plane.

MIRRORS AND PRISMS

Autocollimation mirrors must be front surface mirrors and they must be optically flat (to within a few millionths of an inch). Rear surface mirrors are not suitable because they produce unwanted reflections which deteriorate the sharpness of the reflected image.

The larger the diameter of the mirror, the more suitable it is because it allows a greater tolerance in positioning. It will also reflect more light rays back to the instrument resulting in a strong image. When a small mirror is used, (i.e. smaller than the objective) the reverse is true. Therefore mirrors which are at least the same size as the objective should be used.

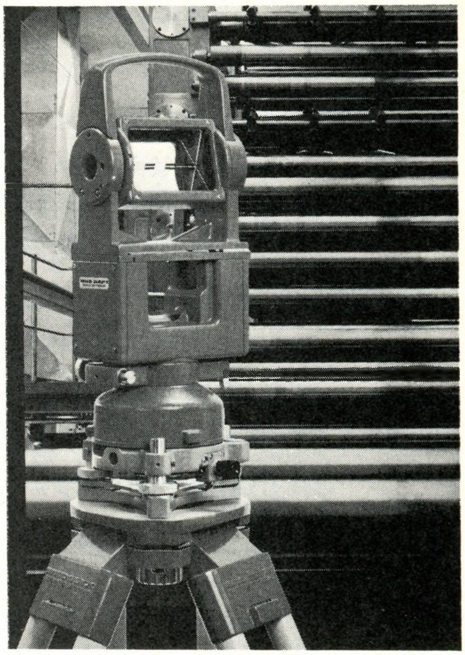
As the distance between the instrument and mirror increases, the reflected image becomes fainter. Therefore it is advantageous to have the mirror as dark as possible.

It must be remembered that in autocollimation and autoreflection, the front surface of the mirror is made perpendicular to the line of sight, and not the surface on which the mirror is located. To make sure that this surface is made perpendicular, it is necessary that the two surfaces of the mirror be parallel. "A mirror target having faces parallel to within 2 seconds must be used."

There are two basic types of prisms used for autocollimation; the 90° roof or Porro prism and the corner prism. The corner prism is not as common in industry, because although the reflected ray returns parallel to its original direction, it is displaced by a certain distance.

The roof prism forms an ideal reference mark for alignment and horizontal angle measurement at different instrument heights. A plane mirror can not be used in such an instance. In the horizontal plane, the roof prism functions as an autocollimation mirror while in the vertical plane it serves as a retroreflector. In other words, accurate orientation of the prism in the vertical plane is not important because the light rays are returned parallel. "Whereas a mirror defines a reference line, the autocollimation prism defines a reference plane." Therefore the advantage of using an autocollimation prism is that autocollimation can always be obtained and horizontal angle measurements can be taken from this vertical reference plane, irrespective of the inclination of the telescope and the height of the instrument.

The Wild GAP1 Autocollimation prism is one of the most recent developments in optical tooling utilizing a 90° prism. It consists of a roof prism mounted in the standards of a theodolite as shown in Figure 5.



Wild GAP1 Autocollimation Prism.

The prism can be tilted to any inclination. The 90° edge of the prism is positioned parallel to the tilting axis. "With the 10″ per 2mm plate level, the instrument can be levelled up precisely, thus setting the roof edge of the prism horizontal." The prism can be roughly aligned to the autocollimation theodolite with an optical sight. The fine adjustment is done with the horizontal tangent screw. The rear surface of the prism contains a scale graduated in millimetres with the zero of the scale exactly on the vertical axis of the instrument. This scale is useful in measuring offsets of the prism or the autocollimation instrument from a baseline. This is achieved by first obtaining autocollimation to the prism and then focusing to the scale and reading the offset. ●

to be continued