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The laserguide system of automatic machine guidance

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Abstract

In this paper a new system for machine guidance (LASERGUIDE) is introduced which exploits the spatial properties of laser beams in combination with arrays of either passive or electrically-active targets. The principle of measurement is explained and this is extended into discussion on a practical level of some possible application areas in construction both above and below ground. The paper concludes with a more detailed examination of operation of LASERGUIDE in controlling the trajectory of a tunnelling machine.

(The measurement technique described in this paper is protected by current UK and international patents.)

1. INTRODUCTION

For many years laser beams have been used for the guidance of machines which perform tasks such as cable and pipe laying, earth-moving and trench excavating as well as various types of underground tunnelling. The common feature of these techniques is that the measurements used for controlling machine trajectory or position are restricted to either one or two-dimensions. In the case of above-ground machines, the laser system can usually provide information on blade height and also in some cases a single degree of tilt; usually across the machine fore-aft axis (roll). For tunnelling machines, the height of some machine reference point in relation to tunnel centre-line can be monitored together with some measure of slew (sometimes called yaw: the left-right forward trajectory).

In the Industrial Metrology Research Unit of the University of East London a new kind of laser based positioning system has been developed for use with construction machines which generates automatically their full 3-dimensional position and spatial orientation in almost real-time.

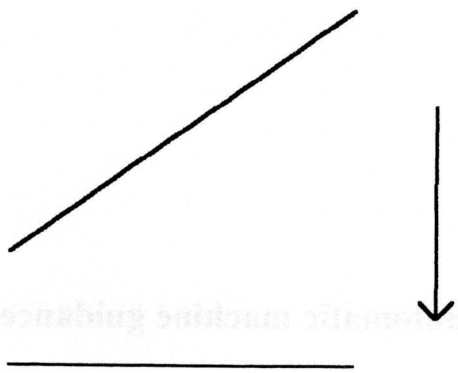

Figure 1

The pair of fanned laser beams have a fixed relative geometry and are projected from the Laserguide scanner so that the beam pattern rotates about a horizontal axis through the instrument. This rotation is internally monitored by a moiré-fringe digital encoder disc in the scanner which carries electronic markers separated by 6 arc minutes and constitutes a vertical angle circular scale. Using time interpolation between these markers spatial direction measures from the scanner can be made to a repeatable accuracy of 1 arc second.

The essence of the measurement technique is that for any suitable target which lies within the 'field of view' of the scanning laser beams two readings of the vertical angle scale will be produced for every rotation of the beams. Both the vertical and horizontal directions of the target from the scanner may be deduced from such a pair of measures taken on the single circular scale. Thus if several targets are encountered in the sweep of the pair of laser beams the full spatial direction vector for each of them as seen from the scanner may be generated almost instantly.

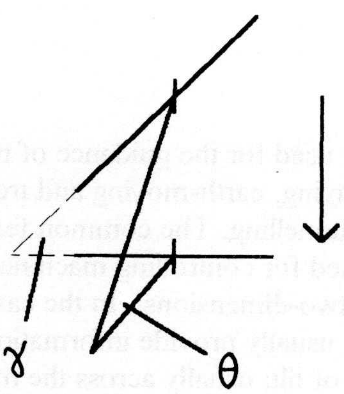

Figure 2

When the scanner is first produced the leading laser beam is set parallel to the rotation axis and the trailing beam set close to 45° inclination to that axis. For the scanner of this discussion, the central rays in the two beams have a fixed included angle 'θ' say, and the nominal 45° tilt angle of the trailing beam has an actual value of 'γ'. Both θ and γ are determined by initial instrument calibration and remain sensibly fixed thereafter.

If an electronic photocell were to be located midway across the width of the laser beams and in the vertical plane which passes through the centre of the scanner projector, say a quadrant form photocell, and the angle disc in the scanner latched at the moment the sweeping first beam crossed the cell centre, a disc direction reading R_1 would be generated. A corresponding reading R_2 for the second beam would also be produced a moment later. Since the photocell is in the central vertical plane of the scanner, it is clear that $R_2 - R_1 = \theta$.

In the case that the photocell is located to the right of the scanner centre-line, the two angular directions on the disc, corresponding to the two points of incidence of the laser beams on the centre of the cell, will be more separated: $R_2 - R_1 > \theta$. Conversely, where the photocell is located to the left of the scanner centre-line, the two disc readings are closer together and now $R_2 - R_1 < \theta$.

The horizontal deflection angle 'φ' of the photocell target with respect to the horizontal datum direction of the scanner may be derived by using Napier's Rule of spherical trigonometry for a right-angled spherical triangle. In this case the relation is $\mathrm{TAN}\ \varphi = \mathrm{TAN}\ \gamma \cdot \mathrm{SIN}(\alpha - \theta)$ where 'α',which constitutes the observable, is the measured angle between the two points of incidence of the beams on the photocell and corresponds to the value of $R_2 - R_1$.

Thus by knowing the value of the system constants 'θ' and 'γ' and by examining the magnitude of the difference between the two latched disc readings and comparing this with 'θ', the corresponding horizontal deflection of the photocell target from the laser scanner datum centre-line can be determined. The inclination or depression in a vertical plane of the target is given directly by the first beam disc reading R_1. Full spatial direction measures to a point target can thus be obtained for every full circle rotation of the scanner and the rate of direction data update is limited largely by the speed of the electronic counters used in the interpolation of the moiré disc pulses. For this application a practical limit is about 20 Hz.

By providing a fixed and known array of targets on the machine to be guided, the set of direction measures obtained by Laserguide can be used in a tracking algorithm which results in a determination of spatial position of each of the targets in the 3-dimensional reference frame set by the instrument. This can be translated into position co-ordinates for the machine centre as well as it's spatial attitude.

In the case of machines which do not follow an essentially straight path, there are two approaches which can be used. The first and probably simplest modification to the Laserguide design is to turn the instrument through 90° so that the laser beam pair forms a V-shape which sweeps in a 360° horizontal circle. In this case the extent of the beams in the now vertical plane may have to be increased. An alternative design is to provide an additional circle scale set in the horizontal plane of the instrument and where the output from the vertical disc encoder will enable the instrument to 'track' the target array. In this case the readings from the horizontal encoder circle will be combined with the 'fine' readings of horizontal deflection ϕ.

Two kinds of target have been used with Laserguide prototypes. Active targets formed by quadrant photoelectric cells have been disposed in a random yet fixed and known spatial array on a tunnelling machine, but in such a case it is necessary for the instrument encoder 6-minute angle pulses to be transmitted to the machine on an infra-red beam so that the position data processing can take place on the machine itself. Alternatively, and preferably, the target array is formed by glass corner cube prisms which reflect the scanning laser beams back to the instrument where the position calculations take place. This data can then be communicated to the machine either by a UHF radio or infra-red data link and enjoys the advantages of a less stringent time regime and the facility of error detection protocols.

Laserguide is particularly suited to control machine operations which occur along a fairly predictable trajectory such as cable or pipe-laying, trenching, paving and road surfacing. The provision of a pre-measured array of glass corner-cube prisms retro-fitted to the rear of the machine will enable continuous monitoring of the machine position and it's immediate trajectory. All of this information can be generated once every second of time and it may be used to provide an immediate update to the driver through displays in the cab or to form part of a closed-loop control system for the machine drives or hydraulics.

Laserguide offers a further and significant practical advantage over other techniques of machine guidance in that it is able to apply a simple control of it's own spatial attitude without the need for sophisticated self -levelling systems. This relies on the fact that Laserguide will measure the spatial direction of all targets which appear in it's field of view for every sweep of it's laser beams. Thus by placing a triangular array of three prisms on a fixed frame to one side of (or above or below) the sight line to the machine targets and away from the direct influence of the operations a set of reference directions is defined for the Laserguide computer. When operations are about to commence the Laserguide is shown only these reference prisms and their directions are stored in memory. The stability of these directions are checked for every sweep of the beams and any apparent changes are attributed to angular movements of the instrument itself. From the known geometry of the reference targets the respective axial rotations of the Laserguide instrument are calculated. These are applied as corrections to the machine target direction measurements. It is easy to arrange for automatic switch-off if these reference directions change by more than a pre-determined amount.

A prototype Laserguide was tested by British Coal at Bretby colliery in Staffordshire over a period of some eighteen months. With an array of three glass prisms fitted to the back of the machine, the horizontal range of the machine was measured to an accuracy of 5 cm at 120 m; the height to +/- 5 mm and the cross tunnel position likewise to +/- 5 mm. In addition, the pitch roll and slew of the machine was determined to better than +/- 3 arc minutes at this range: these measures were repeated by the instrument every second.

In this particular application the array of reference or control targets for Laserguide provided two important functions. In the first place the 'coat hanger' of three prisms was fixed to the tunnel roof some 20 metres in front of the Laserguide instrument and the repeated direction measures made to it's prisms provided the necessary continuous monitoring of the attitude of the instrument in it's roof mount and automatic correction to the machine guidance data as described earlier.

In addition, the reference frame of three prisms enabled very efficient re-siting of the Laserguide instrument closer to the tunnelling machine as it progressed. Where a roof mounted visible beam laser is used for tunnel alignment and machine control the process of dismounting, re-siting and more importantly realigning the beam in it's new location can take the surveyor up to eight hours. With Laserguide the process can be undertaken in some 20 minutes.

In essence, the continuous direction readings made by the instrument to the individual prisms of the reference frame have updated it's own spatial attitude in the tunnel and so it is ready for the transfer of position to take place. This is commenced by advancing the three prism reference frame to a forward position in the roof which is closer to the rear of the now distant tunnelling machine. The continuing measures made to the reference prisms in their new location are used by a 'tracking' algorithm to provide XYZ co-ordinates for these prisms in the global co-ordinate frame used by Laserguide and based on the tunnel geometry.

The Laserguide instrument is now advanced to some 20 metres behind the reference frame and commences to measure the apparent directions of it's prisms which are at known spatial positions in the tunnel. This new data is now processed by a 'resection' algorithm which provides both the XYZ position of the Laserguide instrument together with the attitude of it's internal axes. It is now ready to continue with the machine guidance process.

It may be useful to distinguish more clearly between the two analytical processes referred to as 'resection' and 'tracking' since they are fundamental to any process of remote machine guidance. In this connection it is necessary to consider the relationship between the relevant co-ordinate systems used to describe spatial position. Where objects are to be moved in space and their paths monitored by remote measurement a global co-ordinate system is normally defined. In the case of a construction site the control site survey is used to determine this and it is realised in practice by a network of monuments or semi-permanent markers. In tunnels the control markers are usually fitted to the roof or crown of the tunnel and it is common to use the centre-line of the tunnel as one of the co-ordinate axes of the global rectangular co-ordinate system. When a rigid array of points is used within the global framework, such as the Laserguide prisms, they are given temporary local co-ordinates based on the geometry of the frame on which they are mounted.

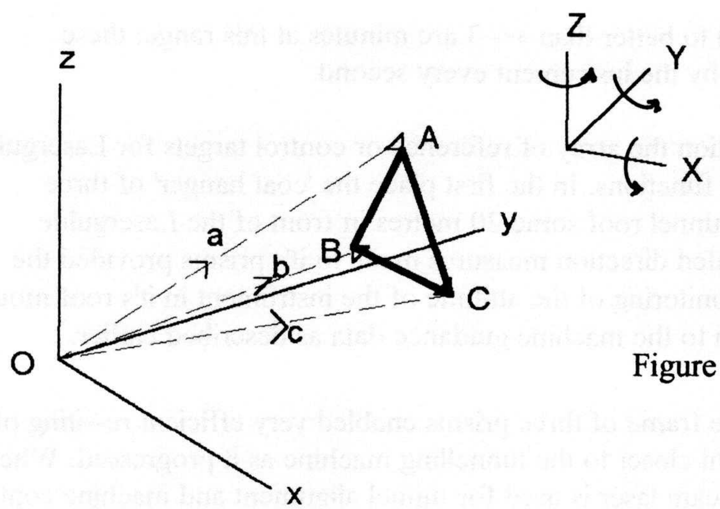

Figure 3

In the figure is shown a three target array **ABC** *with spatial position defined by the* co-ordinate system **XYZ**. Observations are made to individual targets which generate respective direction vectors **abc** from an instrument at **O** which is at the origin of the independent instrument based co-ordinate system **xyz**.

Now if the process of *resection* is taking place the targets **ABC** will be co-ordinated in the global system **XYZ** and the observing instrument will occupy an unknown position at **O** the origin of it's own local co-ordinate frame. From a knowledge of the direction vectors to the respective targets whose global position co-ordinates are known, it is possible to calculate the position of **O** in the global system and to orientate the instrument axes with respect to those of the global reference frame.

Conversely, in the process of *tracking* the position of the instrument at **O** will already be known in global co-ordinates (now assumed to be based on the **xyz** frame in the figure) and the targets will have their own independent local co-ordinate frame, **XYZ** in the figure. Again the individual direction vectors to the targets from **O** coupled with the knowledge of the internal relative positions of the targets will enable their co-ordinates in the global frame **xyz** to be calculated.

CONCLUSION

Both the resection and tracking algorithms have been developed in the Industrial Metrology Research Unit and these are believed to be unique. They complement the operation of an automatic spatial measurement system such as Laserguide and help to maintain both accurate and repeatable measures over long periods of time.