A SYSTEM FOR DETERMINING THE LOCATION OF CONSTRUCTION EQUIPMENT ON THE WORKING SITE

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SUMMARRY

It is known that mobility of future robotic construction plants, which is their main function, is ensured by the possibility of high-precision positioning and by the orientation capability of a movable robot in reference to a stable (engineering type) system of coordinates related to the parameters of the site. We think that in the conditions of a construction site, modules for measuring the position of the construction plant should comprise cheap and reliable systems adapted, as much as possible, to use geodetic beacons and the features of construction methods. This article describes a unique system of positioning the mobile generel-purpose construction plant relative to navigation beacons placed on the site in accordance with the construction design. The system comprises a laser transmitter which is placed on the plant at a fixed point and has a built-in photodetector, and a plant-borne computer with a console connected to it for initial geometric data input. The transmitter forms two sectoral laser planes crossing each other at a specified angle, and ensures their synchronous rotation about their longitudinal axes. At least three beacons, i.e. corner reflectors, are placed on the site. They return laser radiation to the transmitter's photodetector whereby their angles of view can be measured. From the data obtained, the computer will determine the position of the plant and its angular orientation in space. The article deals with the basic principle of building the system and with the experimental developments. Some examples of its practical application are also described.

I. INTRODUCTION

In many cases where mobile robotic plants are used to solve construction problems, these plants continually need an accurate information about their position in the working area limited by certain geometric parameters, in order to control the movements of their tools in space. This generally implies the need for the robot to have appropriate navigation equipment for measuring its coordinates with respect to the axes of the construction site, and a set of fixed beacons related to it which are also used to determine the area where the robotic plant can operate.

Practically all contactless (remote) methods of determining the space coordinates of the object are based either on measuring distances to reach it from at least two points apart from each other and then solving the resultant triangles by three known sides, or on computing the measured angles of view for a certain number of reference points if their positions are known. These methods can be implemented in many different ways such as the use of acoustic equipment [1], the optics with light polarization [2], infra-red sources [3], and others. However, if we want to build an anti-interference, high -precision navigation system for the mobile robotic plant to operate on a big site, it is practical to use laser means for this purpose.

A few laser-based positioning systems for construction plants are known. For example, in the system [4,5], the laser transmitter is placed on the construction site at a point with known coordinates; the transmitter has an automatic tracking device which uses the laser beam to track the reflector mounted on the plant. The position of the plant is computed by measuring distances to the reflector and its angular position with respect to the laser transmitter, the information being transmitted by a radio link to the machine.

When using two laser transmitters [6,7] placed on the site with known coordinates and several sectional photodetectors mounted on the construction plant, a self-contained navigation system can be implemented. For this purpose, laser beams from the sources are scanned relative to their verticals with pre-determined angular velocities, and from successive time intervals measured between impacts of radiation from both lasers on the photodetectors, their angles of view are recorded. From known distances between vertical axes of the photodetectors, plane coordinates of the construction plant are computed, and the indexes of photodetector irradiated sections will characterize the vertical coordinate of the construction plant.

A more advanced, from our viewpoint, is the navigation system [6,8,9,] with one laser transmitter placed on the robotic plant where the source is stabilized with respect to the gravity vertical. On the construction site at points with known coordinates, a few beacons-reflectors are placed,for example, corner reflectors or other type reflectors having, in particular, an elongated shape [9], and the laser beam is scanned relative to the source centerline; from reflected radiation, angular positions of the beacons are recorded and on the basis of information so obtained, plane coordinates of the construction plant are computed. Where point beacons are used, the plant elevation is determined from the deflection of beacon planes from the laser beam sweep.

In order to expand the information zone for plant operation, especially in height, and to get rid of laser transmitter stabilizing systems, we have proposed the scanning of laser beam swept, for example, by a cylindrical lens to form a sector. The vertical coordinate of the plant has been computed in this system using the information about its heeling and pitching angles received from additional sensors. However experimental studies on this system have shown that its accuracy is unsatisfactory where the plant makes frequent movements on bumpy surface, primarily due to inertia errors of angle sensors.

The unique system developed by us [10] does not have the above drawbacks, it is simple and cheap and includes only a rotating laser transmitter with a built-in photodetector receiving the radiation reflected from the beacons, and a computer module. Its operation is based on sweeping the beam to form two intersecting sectors and scanning them simultaneously.

II. BASIC PRINCIPLE

The positioning system for the construction plant is based on a new method of determining simultaneously the azimuth and elevation angles for each of the beacons placed on the site at points with known coordinates.

In the system, the rotating transmitter forms and provides a synchronous rotation of two sectoral laser planes about its longitudinal axes. These planes cross each other along the line perpendicular to the transmitter's axis of rotation, one plane passing through the axis of rotation and the other being inclined at an angle of δ to the first plane. The position (X_j, Y_j, Z_j) of the beacons M_j, $j=1,3$; on the site is known.

Fig. 1 shows the geometric basis for determining the elevation angle σ_j for the j-th beacon with respect to the plane of rotation of laser sectoral planes intersection line, where:

XOYZ – an engineering (earth) system of coordinates (ECS), for the construction site;

R – a laser radiation transmitter placed on the construction plant at a point with coordinates (X_0, Y_0, Z_0) to be found;

O_j^v – a point where the laser radiation sectoral plane passing through the axis of rotation crosses the j-th corner reflector placed on the site at the point M_j with coordinates (X_j, Y_j, Z_j);

RO – laser planes intersection line;

O_j^e, O_j^r – a trace of the point where the second laser radiation sectoral plane crosses the same corner reflector placed at the point M_j (X_j, Y_j, Z_j) and projection of this trace onto the plane of rotation of line RO;

ν_j – a difference in the angles of arrival (phase lag) of reflections from the j-th corner reflector of laser radiation by the first and second sectoral planes during their simultaneous scanning;

δ – a fixed angle between the first and the second laser sectoral planes;

D_j – a distance between the laser radiation transmitter and the j-th beacon,

whence by solving simultaneously the rectangular triangles ROO_j^v and ROO_j^r we shall find the elevation angle σ_j for the j-th beacon with respect to the plane of rotation from the relationship:

$$\sigma_j = \operatorname{arctg}\left\{\frac{\operatorname{tg}(\nu_j)}{\operatorname{tg}(\delta)}\right\} \qquad (1)$$

If provision is made to stabilize the vertical axis of the construction plant or laser transmitter with respect to the gravity vertical, its position on the site can be determined easily by solving the superposition of the three tasks:

- the coordinates (X_0, Z_0) and distances D_j to any j-th beacon in plane will be computed from their angular position Φ_j (azimuthal) in the scanning plane by one of the known methods [11, 12];

- the orientation α of the constraction plant (Fig.1a) on the plane XOZ is determined, for example, from the formula:

$$\alpha = \mathrm{arctg}\left(\frac{Y_0 - Y_1}{X_0 - X_1}\right) - \Phi_1 \qquad (2)$$

- the elevation Y_0 is found from the difference in level with respect to any j-th beacon with the coordinate Y_j as follows:

$$Y_0 = Y_j + D_j * \mathrm{tg}\ (\sigma_j) \qquad (3)$$

With a non-stabilized transmitter, the problem of finding the location of the plant becomes more complicated and needs special consideration.

III. GENERAL CASE OF COORDINATE MEASUREMENT FOR A NON-STABILIZED CONSTRUCTION PLANT

Given below are the expressions for determining the position of the construction plant relative to the axes of the engineering (non-rotating) system of coordinates (ECS) using the measured angles of view σ_j and Φ_j of the markers in the coordinates system related to the axes of the plant (RCS).

Suppose we know the coordinates of all the i,j markers in the engineering system of coordinates (ECS) (Fig.2):

$$\bar{R}_j^g = \begin{vmatrix} X_j^g \\ Y_j^g \\ Z_j^g \end{vmatrix} \qquad (4)$$

and also the vectors $\bar{D}_{ij}^g = \bar{R}_i^g - \bar{R}_j^g$ of distances between them.

In the coordinate system (RCS) related to the axes of the plant, the position of each of the j-th reflectors can be expressed in terms of the angles σ_j and Φ_j as follows:

$$\bar{R}_j = \begin{vmatrix} X_j \\ Y_j \\ Z_j \end{vmatrix} = r_j * \bar{e}_j \ , \qquad (5)$$

where

r_j - the unknown distance from the transmitter to the j-th laser radiation reflector,

$\bar{e}_j$ - the measured unit vector of the j-th marker in the RCS,

$$\bar{e}_j = \begin{vmatrix} \cos\sigma_j * \cos\Phi_j \\ \sin\sigma_j \\ \cos\sigma_j * \sin\Phi_j \end{vmatrix} , \qquad (6)$$

and the distances $\bar{D}_{ij}$ between them can be expressed accordingly as $\bar{D}_{ij} = \bar{R}_i - \bar{R}_j$ or in terms of the radius vectors e_j of the beacons as follows:

$$\bar{D}_{ij} = r_j * \bar{e}_j - r_i * \bar{e}_i \quad . \qquad (7)$$

The relationship between any vectors, in particular, those of the distances, in the ECS and RCS is described by the expression:

$$\bar{D}^{g}_{ij} = M^{t}(\phi,\theta,\gamma) * \bar{D}_{ij} \quad , \qquad (8)$$

where the transformation matrix $M(\phi,\theta,\gamma)$ has dimensions of 3*3,and its elements m_{ij} are functions of the unknown turning angles of the construction plant with respect to the ECS in terms of the course ϕ, pitch θ and heel γ respectively:

$$M(\phi,\theta,\gamma) = \begin{vmatrix} c\phi*c\theta & s\theta & -s\phi*c\theta \\ -c\phi*s\theta*c\gamma+s\phi*S\gamma & c\theta*c\gamma & s\phi*s\theta*c\gamma+c\phi*c\gamma \\ c\phi*s\theta*s\gamma+s\phi*c\gamma & -c\theta*s\gamma & -s\phi*s\theta*s\gamma+c\phi*c\gamma \end{vmatrix} , \qquad (9)$$

the superscript "t" in (8) indicates the operation of matrix transposition.

Expressions (7-8) form a set of 9 equations with 12 unknown quantities which are the elements m_{ij} of the matrix $M(\phi,\theta,\gamma)$ and the distances r_j.

However, since in any transformations by a rotation method the magnitudes of distances D_{ij} remain unchanged, the three equations missing to complete the system will assume, considering (6), the form:

$$\left| \bar{D}^{g}_{ij} \right|^2 = (X_j - X_i)^2 + (Y_j - Y_i)^2 + (Z_j - Z_i)^2 \qquad (10)$$

The solution to the system of equations (10) will give three values of r_j; after substituting them in (7) we shall obtain the distances D_{ij} in the RCS where by the elements m_{ij} of the matrix $M(\phi,\theta,\gamma)$ and, hence, the transmitter's coordinates in the ECS can be found as follows:

$$\begin{vmatrix} X_0 \\ Y_0 \\ Z_0 \end{vmatrix} = \begin{vmatrix} X_{jg} \\ Y_{jg} \\ Z_{jg} \end{vmatrix} - M^{t}(\phi,\theta,\gamma) * \begin{vmatrix} X_j \\ Y_j \\ Z_j \end{vmatrix} \qquad (11)$$

The angular orientation of the construction plant relative to the engineering system of coordinates will be found in this case from the expressions:

$$\phi = \mathrm{arctg}\left(\frac{-m_{13}}{m_{11}}\right) ;$$

$$\theta = \arcsin m_{12} ; \qquad (12)$$

$$\gamma = \mathrm{arctg}\left(\frac{-m_{32}}{m_{22}}\right) .$$

All measurements of the angles σ_j and Φ_j and computations of the position of the construction plant can be performed during one revolution of the laser transmitter.

IV. EXPERIMENTAL DEVELOPMENTS

On the basis of the above principle there has been designed, manufactured and tested a space positioning system for the construction plant.

Fig. 3 shows a diagram of the system where figures indicate the following:

1 – a laser radiation source;
2 – a scanning head with a deflecting system which forms two sectoral laser planes;
3 – a laser radiation detector integral with the transmitter;
4 – a special high-precision measuring unit to measure the actual rotation angle Φ of the scanning head:
5 – a zero laser radiation detector which forms the signals of zero angle reference;
6 – a microprocessor-based computer for data processing;
7 – a system operation control and display unit;
8 – corner reflectors.

An experimental set of the system equipment consists of three main units:

– the laser transmitter with a scanning head, a high-precision angle measuring unit and a zero radiation detector fixed to its body;

– the system operation control and display unit which has on its panel three lamps to indicate the presence of optical contact with reflectors, the display to indicate the transmitter's coordinates Xo,Yo,Zo in millimeters and the keyboard for initial information input.

– the DEC-18637S type microprocessor-based computer to compute and to give the information about the position of the object on its output peripherals in the RS-232 standard.

The transmitter which has a rotating optical head, uses a commercial helium-neon laser with an output capacity of 20 mW. The sweep of the laser beam to form sectoral planes is achieved by means of cylindrical lenses properly adjusted. The nominal rotation speed of the head is 10 rev/s and a means is provided in the equipment to vary it from 4 to 24 rev/s.

In order to achieve high-precision measurements of the angles of view Wj and Gj for reflectors, a unique combined principle of the vernier-type was used; angles are measured with the help of a code optical disk in increments of 2 mrad and then discretization of every such interval takes place; as a result, the overall accuracy of angle measurements in the experiments was as high as 0.01 mrad. In determination of the coordinates Xo,Yo,Zo by this system the error was less than 1.5 mm in the tests where distances from the laser radiation transmitter to beacons were up to 30 m.

V. PRACTICAL APPLICATION

The equipment has been developed to serve as a main component for the navigation system of the plant to automate construction of brick buildings and structures and also, as a system of accurate space positioning of its working tool with respect to geodetic axes of the building. However it is easy to find a great number of other effective applications of the system.

The proposed system enables one to measure space coordinates of the road-building and earth-moving machines (motor graders, vibrating rollers, land reclamation machines and other mobile plants) for the automatic monitoring of their position and automatic control of their movements on the construction site.

With this system it is possible to automate a great number of material handling operation, in particular those using helicopters as well as warehousing operations using transport robots, and to make it easier to control the position of the working tools or instruments of other robotic plants.

VI. CONCLUSION

The analysis of the above shows a great potential of this self-contained positioning system for the construction plant on the site in terms of its practical application.

Our system has the following main advantages:

- on the object whose position is to be controlled, it is sufficient to have only one laser transmitter station;
- the only movable part in the system laser transmitter, like in most such devices, is an optical head;
- the additional features on the traditional laser transmitter with a rotating optical head may be quite simple including the sweep of the laser beam to form sectors, recording the signals returned from corner reflectors and measuring the actual head rotation angle (this is being done in some laser devices);
- for operation of the positioning system it is sufficient to place in the area around the plant a chain of only three beacons with known coordinates, and the beacons may have different elevations.
- the equipment of the system is fully independent; its hardware does not require any additional communication means; the coordinates of beacons are loaded in the computer memory from the console before the work starts, and they are stored there as long as required.

All the aforesaid makes the proposed system potentially reliable and safe in use.

The possible measurement range of our system will be limited by the capacity of laser transmitter, the sizes of sectors formed by laser beam and by the distances to beacons. Naturally, there should be no permanent obstacle between beacons and the transmitter.

Our future developments will be aimed at improving the experimental model of the system for its practical application in construction robotics, and searching for its new applications (taking into account the specific restrictions imposed on the use of such equipment).

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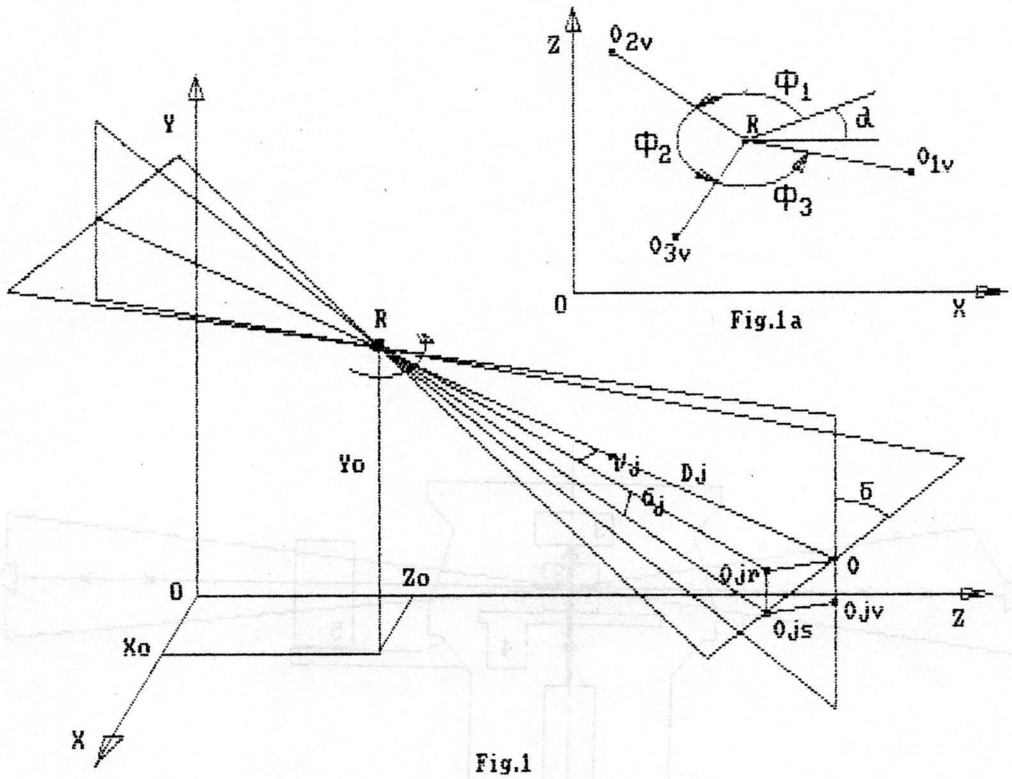

Fig.1a

Fig.1

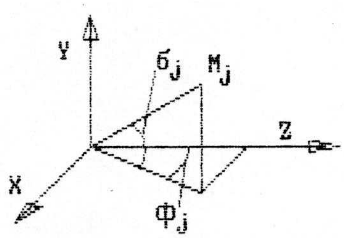

Fig.2a

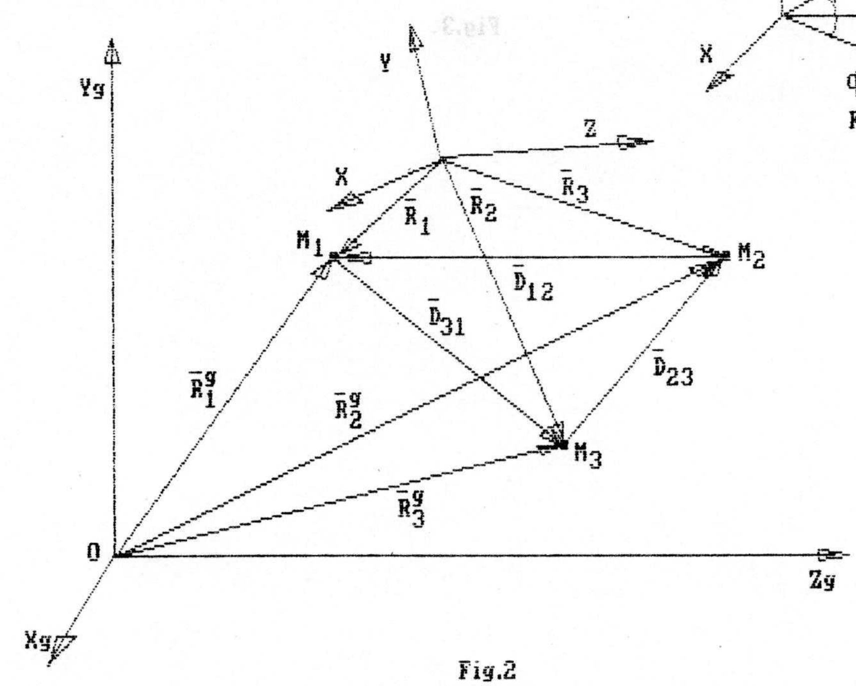

Fig.2

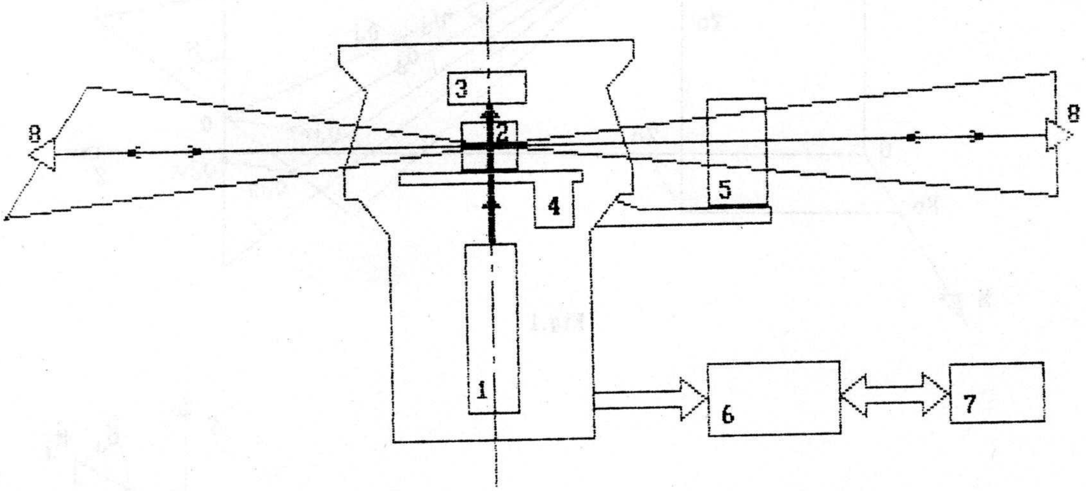

Fig.3