SIREM: THE ABSOLUTE LOCATION OF CIVIL ENGINEERING EQUIPEMENT

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ABSTRACT

After having shown the necessity to locate in the three dimensions the civil engineering machines whose tasks are to be automated, the authors recall the advantages and disadvantages of the different existing systems and methods. The main point of the paper is about an original location system using an on-board measuring device and ever-standing luminous grade stakes. In a first step we explain the resolution method assuming the vehicle does not move during the data acquisition and set out the obtained simulation results in terms of algorithms and sensitivity of the latter to measuring errors. Once the static problem solved, we propose a resolution principle for the dynamic location using the previous results combined with a behavior model of the vehicle and an estimator. The paper ends with the description of the real system being built and with the presentation of the future steps of the SIREM program

1- REQUIREMENTS

1-1 Introduction

The robotization of public works equipement is a long-term problem which will be solved by the mastering of the following successive phases:
- location and execution parameters real-time acquisition phase,
- operating aid phase,
- equipement robotization phase,
- jobsite robotization phase.

The existing equipement provided with suitable sensors, an on-board data processing system, with slaved actuators, could be robotized according to the diagram shown in figure1 [GOY-86].

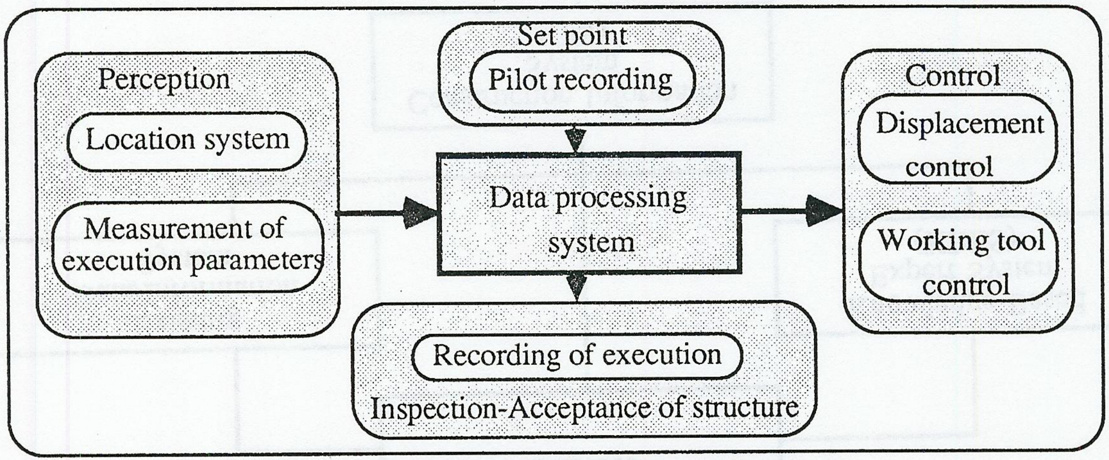

Figure 1- Robotized equipment main functions

Contactless and real-time measurement of location parameters appears clearly to be an essential requirement [PAU-85]. It is thus possible to consider a real CAM system working on the data already used during the CAD study [EVA-86], [BAE-89].

1-2 Specific problem of highway equipment location

A road can be regarded as an object, initially theoretical, but then real and rigorously stable in space, on which a certain number of mobile machines work successively during its construction and its maintenance [HER-88].

About ten tasks, carried out by specific equipment, require the knowledge of position parameters. The number of these parameters varies usually between two (ex:X,Y for a compactor) and four or even more (ex:X,Y,Z and cross-slop for a paver). The precision required ranges from a few dm to a few mm (in Z for paving).

The specific points of our problem are:
- the existence of a large base of high-performance machines and tools,
- a well-defined environment,in most cases well structured,
- a field of equipment action which is limited and extended,
- the presence in most cases of a large number of machines on the jobsite,
- the need in most cases to know the position in the three dimensions,
- work carried out exclusively outdoors,
- economic conditions excluding costly approaches.

Considering the nature and the specificities of the problem involved, it is necessary for each machine to be located with a common reference. An on-board sensor reading fixed markers on the job-site currently appears to be the solution [HER-88], [YAM-88], [VOS-89].

2- EXISTING FACILITIES

2-1- Already used on the jobsite.

- Guide wire.

Although awkward and archaic, this method is at present the means most currently used when one wishes to level or spread a layer of materials on an evolving profile positioned in absolute value. On certain machines, the wire line is also used for directional guidance.

- Laser plane.

A detection cell is installed on the equipement tool and a position control device, acting on the tool command, keeps the cell within the plane. Under current utilization conditions, this technique can be used only for the construction of flat surfaces of the type found in parking areas and airports. By perfecting the equipment and completing it with an X-Y location system, it would be perfectly possible to have the tool carry out any type of profile Z=f(X,Y) previously recorded [TAT-88].

- Odometry.

Odometry is relative location technique that begins to be used on some existing machines. Combined with angular deviation information, travelled distance information can provide an estimation of the vehicle position. Because of their tendancy to drift and their need of periodic recalibration on reference points, relative location techniques only partially solve the problem involved.

2-2- Location systems existing or under development.

To solve the location problem, two principles can be used; distance measurement (telemetry) or angles measurement (goniometry), and three information vectors can be chosen; ultrasonic, light (coherent or noncoherent) or micro waves. Ultrasonic waves are too limited in range and precision for most cases of equipment location [TSA-85], [SAL-88]. Microwaves are well suited to distance measurements and light waves to angle measurements owing to their very good directivity. Optical systems also appear to be more precise in the present state of the art [EVA-86].

To fulfill the location function in the plane, optical goniometry (X,Y,Θ) [VOS-89] is competing with microwave telemetry (X,Y). In space, the GPS-NAVSTAR system (X,Y,Z) appears to be a valid one, if it fulfills its promise with respect to precision and cost [BAE-89]. At the present time it is not suited to our problem, its real-time precision is far too weak.

Among the systems under development we know, only the CSTB project [SAL-89] (intended for building industry jobsites) and the LCPC project [PEY-89] can deliver the six degrees of freedom of the mobile unit.

3- THE SIREM PROJECT

3-1- Objectives

In light of the specific nature of the problem described above, the SIREM programme is designed to meet the following main objectives:

- equipment easy to use, robust and inexpensive,
- determination of the six degrees of freedom of the mobile unit on which the sensor is fixed in relation to an absolute reference materialized by stationary markers,
- real-time measurements and calculations,
- mobile speed range: from 0 to 6 km/h,
- spacing of markers: about 50 m,
- location precision, varying according to speed:
    - . in X,Y: from 10 cm to 50 cm,
    - . in Z: from 10 mm to 50 mm,
    - . in attitude: from 0.1 to 0.5 degree,
- location calculation rate: at least every meter travelled.

3-2- General principle

The mobile unit is equipped with a rotating camera having a linear detector placed parallel to the axis of rotation, the optical center of the lens being on the rotation axis. This sensor is thus capable of measuring, for each light ray coming from a marker, the angle of rotation (azimuth) and the angle defined by the image of the marker on the detector (height). With each rotation and throughout the movement of the mobile unit, the sensor reads the three markers positioned in a reference, giving six measurement. From these and from a vehicle behavior model, the six location parameters are extracted.

4- DIRECT STATIC PROBLEM [LEC-89]

Let's consider an absolute reference frame R_0 in which are defined the three beacons positions. The vehicle, equiped with its sensor, is characterized by its frame R_M:

Origin: point M middle of driving wheels axle
X_M axis : parallel to the speed vector
Z_M axis : perpendicular to the wheels plane.

The mobile is located in R_0 by the following location matrix:

$$^{0}T_M = \begin{bmatrix} s_x & n_x & a_x & x_m \\ s_y & n_y & a_y & y_m \\ s_z & n_z & a_z & z_m \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (1)$$

in which $s=[s_x,s_y,s_z]^T$, $n=[n_x,n_y,n_z]^T$, $a=[a_x,a_y,a_z]^T$ are the unitary vectors of R_M and x_m,y_m,z_m the coordinates of M in R_0.

The position of rotating sensor fixed on the mobile is characterized by its frame R_C:
Origin: optical center, which coordinates in R_M are x_c, y_c, z_c, (point C in figure 2)
X_C axis : parallel to X_M axis,
Z_C axis : rotation axis of the sensor, parallel to Z_M axis.

Let ${}^{M}T_C$ be the transformation matrix from R_C to R_M and let B_1, B_2, B_3 be the three beacons with respect to frame R_0, the sensors will give (see figure 2):

$\lambda_1, \lambda_2, \lambda_3$ the azimuth angles

$\sigma_1, \sigma_2, \sigma_3$ the height angles.

The static location problem consist in calculating the components of ${}^{0}T_M$ using azimuth and height angles of the beacons, assuming that the vehicule does not move during one reading cycle.

The positions of three beacons in R_0, the transformation matrix ${}^{C}T_M$, and the angles λ_i, σ_i are known. From figure 2 we calculate the coordinates of beacons in sensor frame R_C:

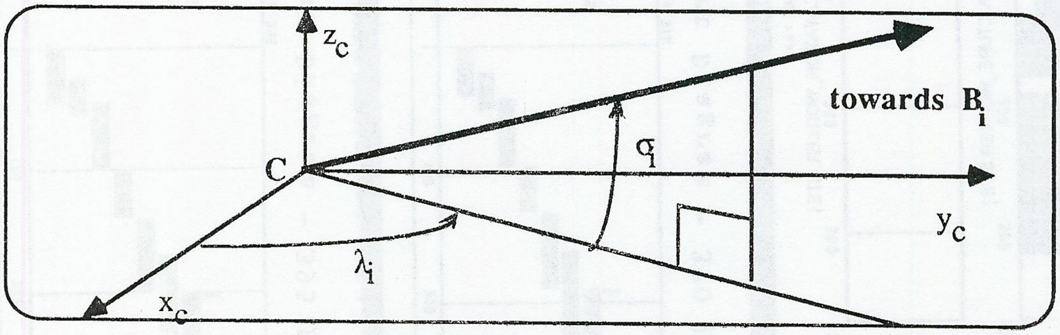

figure 2- The sensor frame

for i = 1,... 3, let: x_{bi}, y_{bi}, z_{bi} be the coordinates of B_i in R_C
$b_i = |CB_i|$ be the distance of B_i to the optical center

then:

$$x_{bi} = b_i \cos\sigma_i \cos\lambda_i$$
$$y_{bi} = b_i \cos\sigma_i \sin\lambda_i \tag{2}$$
$$z_{bi} = b_i \sin\sigma_i$$

Let the distances between the three beacons be: $d_{23} = |B_2B_3|$, $d_{31} = |B_3B_1|$, $d_{12} = |B_1B_2|$. Because the distances b_i and d_{ij} ($j = i+1$ modulo 3) are invariant in any translation and rotation transformation:

$$(x_{bi}-x_{bj})^2 + (y_{bi}-y_{bj})^2 + (z_{bi}-z_{bj})^2 = d_{ij}^2 \tag{3}$$
$$b_i^2 = x_{bi}^2 + y_{bi}^2 + z_{bi}^2 \tag{4}$$

After simplification equations (2), (3), (4) become :

$$b_i^2 + b_j^2 - \alpha_{ij}\, b_i\, b_j - d_{ij}^2 = 0 \tag{5}$$

with: $\alpha_{ij} = 2\,(\cos\sigma_i \cos\lambda_i \cos\sigma_j \cos\lambda_j + \cos\sigma_i \sin\lambda_i \cos\sigma_j \sin\lambda_j + \sin\sigma_i \sin\sigma_j)$ (6)

The resolution of the non-linear system (5) gives the three b_i. These three values are reported in the équations (2). So we get the three markers coordinates in the sensor frame R_C. Then the ${}^{0}T_M$ components calculation can be carried out in the following way: Let R_B be an intermediate frame bound to the three markers, defined by:

Origin: B_1, which coordonates are known in R_0 and R_C.
X axis: line B_1B_2.
Z axis : perpendicular line to markers plane.

Let s_b, n_b, a_b be the unit vectors of R_B, then:

$$s_b = \frac{B_2 - B_1}{|B_1B_2|}, \quad a_b = \frac{s_b \wedge v}{|s_b \wedge v|}, \quad n_b = a_b \wedge s_b, \quad \text{avec} \quad v = B_3 - B_1 \tag{7}$$

The component calculation of these vectors can be carried out using (7), first in R_0, then in R_C. So we can calculate ${}^{0}T_B$, the transformation matrix from R_B to R_0, using the

B_i coordonates in R_0, and, in the same way, using the B_i coordonates in R_C, we can calculate ${}^CT_B$ the transformation matrix from R_B to R_C.

So the final location matrix ${}^0T_M$ is given by:

$$ {}^0T_M = {}^0T_B \cdot ({}^CT_B)^{-1} \cdot ({}^MT_C)^{-1} \qquad (8) $$

From the original data which are the marker coordinates, the successive phases of the static problem resolution are:

Six angles measurement acquisition during one sensor rotation: λ_i, σ_i
b_i distances and ${}^CT_B$ calculation
${}^0T_M$ calculation
wait till the next acquisition.

5- THE DYNAMIC LOCATION

5-1- Principle

The dynamic location problem consists in the calculation of the ${}^0T_M$ location matrix while the vehicle is moving. This calculation (figure 3) needs to use a dynamic model giving the equipment behavior between two successive acquisitions.

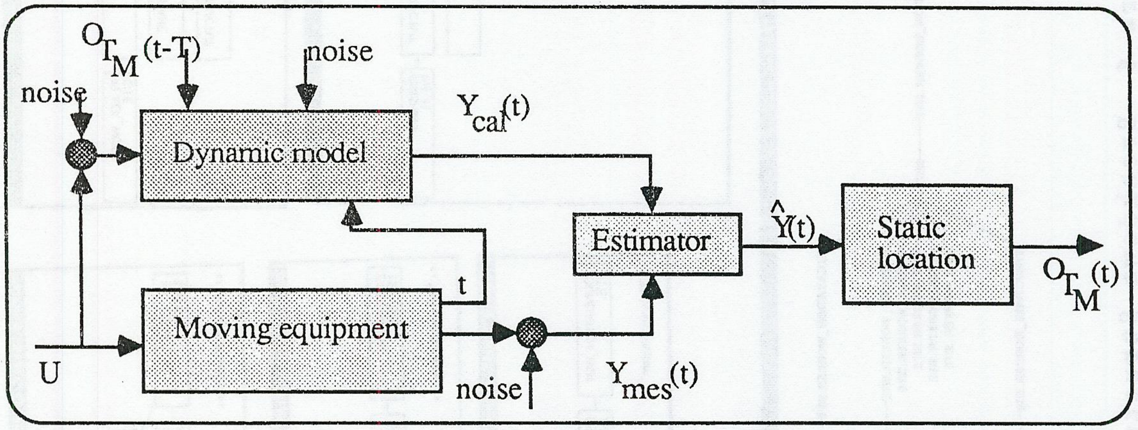

figure 3- Dynamic location synoptic diagram.

The role of the dynamic model is to compute the values of λ_i, σ_i, (i=1,2,3) at time t, which corresponds to the acquisition of λ_k, σ_k for beacon B_k. The equations of the model, with $Y = [\lambda_1, \sigma_1, \lambda_2, \sigma_2, \lambda_3, \sigma_3]^T$, are written as:

$$ \dot{X} = F(X,U,t) \qquad Y = G(X,t) \qquad (9) $$

where X is the state vector, U is the control vector and Y is the output vector.
The input data is:

- the location matrix at time t-T: ${}^OT_M$, where T the elapsed time since the last acquisition,
- the position of the beacons in R_O,
- the model of the control law $U(\tau)$, $t-T \leq \tau \leq t$
- the model of the running surface (locally a plane).

Computation of the values λ_i, σ_i is a four- step process:

1- Evolution of the mobile during time T on the local plane using the control law,
2- Equation of the local plane with respect to frame R_0,
3- Location of the mobile unit in R_0 at time t,
4- Computation of the output vector in R_0.

5-2- Evolution of the mobile unit on the surface

The mobile unit is a two-wheel drive vehicle (figure 4). The two wheels being independant and the speed nearly a constant, the first derivatives of the rotation angles of the wheels can be chosen as the components of the control vector U.

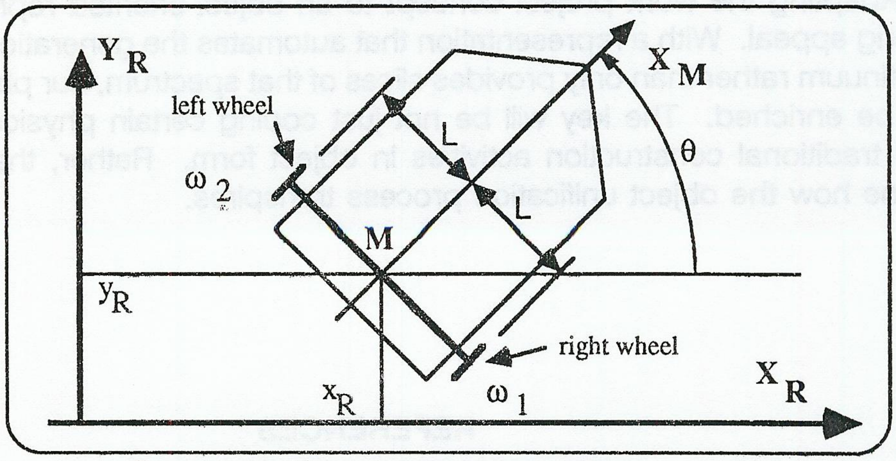

figure 4- Mobile unit on running surface

The equations of the movement of the mobile unit can be written in a frame R_R bound to the local running plane. The following notations will be used:

$M(x_R, y_R)$: middle point of the wheels axle,
$2*L$: distance between the wheels,
r : radius of a wheel,
ω_1, ω_2 : angular speeds of the right and left wheel respectively,
θ : orientation angle of the mobile with respect to axis X_R.

Then the vector $V_c = [\, x_R, y_R, \theta]^T$ is a configuration vector for the mobile unit and the equations of the movement can be written as:

$$\left[\overset{\circ}{V}_c\right] = \frac{r}{2} \cdot \begin{bmatrix} \cos\theta & \cos\theta \\ \sin\theta & \sin\theta \\ L^{-1} & -L^{-1} \end{bmatrix} \cdot [U] \qquad (10)$$

Equation (10) is the state equation of the system. It allows to compute $V_c(t)$ when $V_c(t\text{-}T)$, $\omega_1(\tau)$ and $\omega_2(\tau)$ are known. After computing V_c through integration of (10), it is possible to calculate ${}^{R}T_M$, the location matrix of the mobile in frame R_R.

5-3 Location of the mobile in R_0.

The running surface (figure 5) is defined, in frame R_0, by the position of the so-called "red line" and the cross-slope d. The red line is defined by a point $A(x_A,y_A,z_A)$ and its longitudinal slope p with respect to OX_0. The frame R_R is defined by:

- its origine A
- X_R axis: the red-line
- Z_R axis is perpendicular to running plane

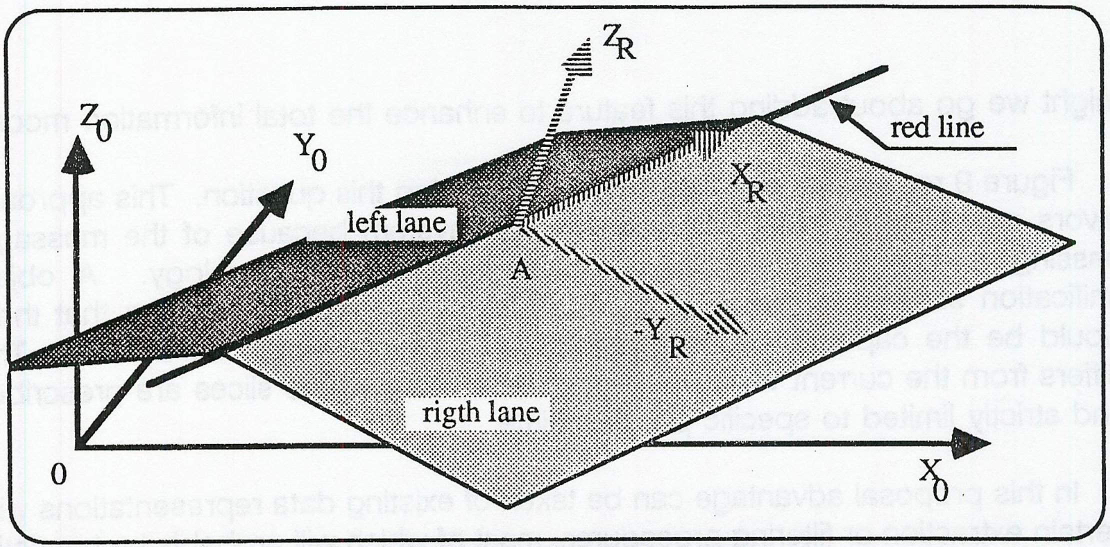

figure 5- The running surface model

The ${}^0T_R$ location matrix of R_R with respect to R_0 is written sas:

$$ {}^0T_R = \begin{bmatrix} c\phi cp & -s\phi cd + c\phi spsd & s\phi sd + c\phi spcd & x_A \\ s\phi cp & c\phi cd + s\phi spsd & -c\phi sd + s\phi scsd & y_A \\ -sp & c\phi sd & cpcd & z_A \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (11) $$

Its is now possible to calculate the position of the model in frame R_0:

$$ {}^0T_M = {}^0T_R \,.\, {}^RT_M $$

The position of the sensor on the mobile is defined by the location marix ${}^MT_C$. Hence the position of the sensor in R_0 is written as:

$$ {}^0T_C = {}^0T_R \,.\, {}^RT_M \,.{}^MT_C. \qquad (12) $$

Since the location ${}^0B_i = [x_i, y_i, z_i, 1]^T$, (i=1,2,3), of three beacons in R_0 are known, then their positions in R_C, ${}^CB_i = [x_{ci}, y_{ci}, z_{ci}, 1]^T$, are given by:

$$ {}^CB_i = [{}^0T_C]^{-1} . {}^0B_i \qquad (13) $$

The output vector Y is computed using the following equations:

$$ \sigma_i = \mathrm{ATAN}\left[\frac{z_{ci}}{(x_{ci}{}^2 + y_{ci}{}^2)^{1/2}}\right] \qquad (14) $$

$$ \lambda_i = \mathrm{ATAN2}(y_{ci}, x_{ci}) \qquad (15) $$

The latter equations make function G of equation (9) computable.

6- CONCLUSION

The SIREM project has been designed to meet the main objectives of the civil engineering equipment location function among wich is essentially the delivering of the six degrees of freedom.

Considering that the static problem is solved by a high-performance and original algorithm , we have now to take into account the movement of the mobile unit between two following acquisitions and to build a prototype sensor system.This will be done in association with a contractor (JEAN-LEFEBVRE) and a robotics firm (CYBERG) inside a two-year contract with the French Research and Technology Minister.

The following step will be SIREM use for the control of a specific equipment.

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