Automation and Robotics in Construction X
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Survey Robot Using Satellite GPS

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Abstract

In Japan, many large projects have been undertaken such as the 513-hectare artificial island of Kansai International Airport and the about 1,000-hectare offshore development project of Haneda International Airport. In the case of civil engineering works involving such a wide area, it is important from the viewpoint of construction management that daily topographic survey be made quickly. GPS is an abbreviation for Global Positioning system, which measures the three dimensional coordinates by receiving microwaves from artificial satellites. By loading this receiver on a vehicle, the survey robot three-dimensionally measures the topography at 0.5 second intervals while the vehicle is running. This robot was used in the reclamation work of Kansai International Airport development project. It has accomplished the three-dimensional topographic survey at 4,000 points in an area of 20 ha in only two hours. One further application of this robot is unmanned surveying for golf courses.

1. INTRODUCTION

Highly accurate measurement methods and advanced management techniques are a critical part of the quest to reduce construction period, labor requirements, energy usage, and cost of large projects, such as airports and land reclamation. This is true for all stages of the work, ranging from surveys and planning to actual execution of the work. For instance, at a large-scale land development site, a swift and simple method of surveying can play a significant role in estimating the amount of cut and fill required. Highly systemized management is needed to properly handle information about complex geological structures and various soils measured in surveys. At a large-scale site, such as an offshore airport or reclamation site, the soft ground is often boggy; yet settlement and ground behavior have to be managed through fill geometry measurements to obtain early estimates of any additional fill needed. Over such vast areas, where efficiency and precision are the determining factors of successful work, there is an urgent need for a survey system based on the satellite global positioning system (GPS). A means of integrating such a system into all fields of work management is also being demanded.

This paper outlines part of our response to this need; a robot which can carry out rapid topographical surveys. Its application to the work now in progress at the Kansai International Airport is discussed, along with a brief mention of some other survey robots which may be of interest regarding future unmanned surveying.

2. GLOBAL POSITIONING SYSTEM (GPS)

The global positioning system (GPS) was set up by the U.S. Department of Defense. The ground position is established using a network of 24 satellites about 20,000 km from the earth on six different orbitals, four on each orbital, as shown in Fig. 1.

Two pseudo-microwave signals, called the L1 wave and L2 wave at frequencies of 1.5 GHz and 1.2 GHz, respectively, are continually transmitted from the satellites. These signals carry encoded data giving atomic clock information, ionosphere correction information, and information on the satellites' orbits. This information is coded in two ways: one exclusively for military purposes and the other openly available to the public at no charge.

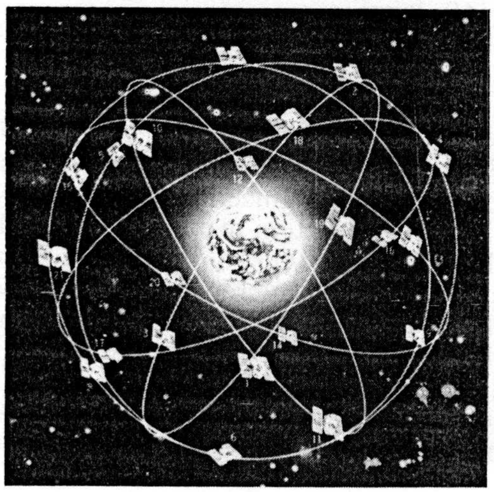

Figure 1. Artist's impression of the GPS satellites and their orbits

3. DYNAMIC GPS SURVEY TECHNIQUE

Conventional survey methods absorb considerable amounts of labor and time because optical surveying equipment requires three to four operators and all analysis has to be done manually. Other survey methods, including the Total Station (Electronic Distance Measurement, EDM) suffers from some constraints:

(1) the need for mutual visual contact between any two survey points;
(2) significant dependence on expertise and experience; and
(3) susceptibility to weather and other factors.

The GPS is currently in use by the Geographical Survey Institute of the Ministry of Construction, which has confirmed the locational accuracy of the system. They are now using it for precise re-mapping of triangulation stations in Japan, however, the static GPS survey methods generally used for reference point surveys take a few hours to measure a single point. In contrast, at a large-scale earthworks site where work is rapidly implemented, topographical surveying of a large area must be completed within a very limited time. For this reason, the normal static GPS method is not considered suitable for earthworks applications.

The dynamic GPS survey technique proposed here, however, enables an instantaneous three-dimensional survey of topography. It has been the subject of various discussions and tests related to survey time and accuracy, and has overcome the conventional restrictions of both software and hardware in this kind of technique. Our new method also reduces the number of survey operators from three or four to only one, and will eventually enable fast, continuous measurements.

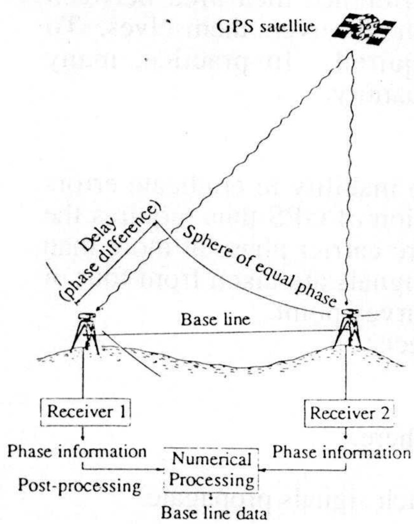

Figure 2. Conceptual outline of relative positioning

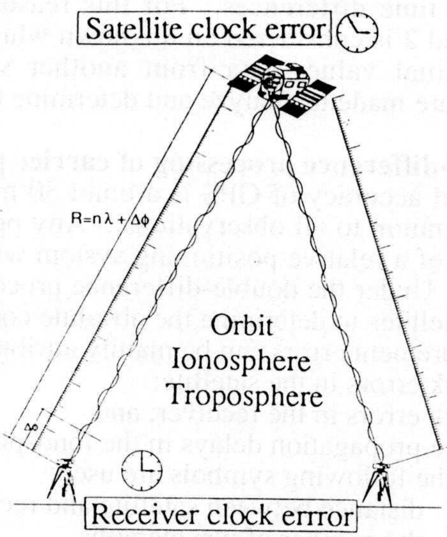

Figure 3. Propagation distance and causes of error

3.1 Principle of measurement

Figure 2 illustrates the idea of relative positioning. This principle is encapsulated in the equation below. ρ_1 and ρ_2 are the distances from the satellite to receivers 1 and 2, respectively.

$$\rho_1 - \rho_2 = \left|\vec{X}_s - \vec{X}_1\right| - \left|\vec{X}_s - \vec{X}_2\right| \tag{1}$$

Where: $\vec{X}_s$: Position vector of the GPS satellite

$\vec{X}_1$: Position vector of the receiver 1

$\vec{X}_2$: Position vector of the receiver 2

$| \ |$: Absolute value of vector

$\vec{X}_1$ and $\vec{X}_2$ on the right hand side of Eq.1 are unknown values with three components, while $\vec{X}_s$ is a known value with three components contained in the orbital information from the GPS satellite. If one of the two receivers is at a known point, the number of unknown values is reduced to three. Since the left hand side is actual data from a satellite, data from three different satellites gives three versions of Eq. 1, each of which can be solved for three unknown values. That is, a receiver in an unknown location can be positioned. However, the collected data contains other information, including the phase difference between the signal received from the GPS satellite at two receivers. This phase difference results from the geometrical relationship of position between the satellite and the two receivers, but it is also influenced by propagation delays in the ionosphere and troposphere, delays within each receiver, and time differences. For this reason, the phase difference measured between receivers 1 and 2 is considered an unknown which depends on the receivers themselves. To obtain its actual value, data from another satellite are required. In practice, many observations are made to analyze and determine this unknown quantity.

3.2 Double-difference processing of carrier phases

The normal accuracy of GPS is around 30 m because of the inability to eradicate errors which are common to all observations,. Any practical application of GPS thus requires the development of a relative positioning system which can measure carrier phase at more than one receiver. Under the double-difference processing system, signals are taken from four or more GPS satellites to determine the absolute coordinates of a survey point.

The measurement errors can be mainly attributed to three effects:

(1) clock errors in the satellite;
(2) clock errors in the receiver; and
(3) wave propagation delays in the ionosphere and atmosphere.

In Fig. 3, the following symbols are used:

R: distance between satellite and receiver, along which signals propagate
n: the number of wavelengths
λ: wavelength
$\Delta\rho_1$: residual phase

To eliminate errors, the following procedure is adopted: First, two receivers receive the carrier phase from the same satellite and the phase difference is calculated. The same measurements are then made using another satellite; the difference in phase measurements is then compared. This double-difference processing allows any errors to be eradicated. Assuming that the absolute phase difference between receiver 1 and 2 (distance from each end of the baseline to the satellite) is $\Delta\rho_1$ and $\Delta\rho_2$, respectively, the difference of positioning, δ, the difference of the phase difference between the two satellites, Σ, is given by the following equation:

$$\Sigma = (n1\lambda + \Delta\rho 1 - \delta) - (n2\lambda + \Delta\rho 2 - \delta) = (n1 - n2)\lambda + \Delta\rho 1 - \Delta\rho 2$$

This double-difference method of processing is essential to high-precision three-dimensional positioning. The positioning data obtained by this method are converted into Japanese geodetic coordinates from WGS-84.

3.3 Characteristics of dynamic GPS surveying

(1) This method allows instantaneous and continuous three-dimensional positioning, significantly improving work efficiency.

(2) This method allows measurements to be made easily by a single person. A quick, simultaneous multiple-point survey of a large area can be implemented by increasing the number of receivers.

(3) This method led to Japan's first case of a continuous survey to 1 cm accuracy.

4. 3-D TOPOGRAPHIC SURVEY ROBOT

The 3-D topographic survey robot, shown in Fig. 4, is a development of GPS technology for use at an artificial island work site. As shown in Photo 1, this robot is a vehicle equipped with a receiving antenna; it carries out continuous topographic surveying while moving around the site. It has performed well at an actual work site, demonstrating its efficiency and precision.

Figure 4. Artist's impression of large-area 3-D topographic surveying using vehicle

Photo 1. Vehicle used for GPS high-speed dynamic positioning

4.1 High-accuracy positioning of dynamic platforms with GPS

In developing a vehicle to carry out highly accurate continuous positioning, a series of tests was implemented to check the basic characteristics of the equipment. Various experiments were then conducted to solve several problems which manifested themselves during this development process.

One characteristic of this system is that only one piece of data is received for each survey point. If signals from the satellite are interrupted for any reason during the survey, errors in the phase data may arise. Such errors, known as cycle slip, must be avoided. The relationship between the velocity of the vehicle and survey accuracy also had to be clarified. The main issues considered in the study were (1) the optimum combination of satellites, (2) the initial setting (selection of a whole number bias), (3) the method of measuring the antenna height, and (4) the optimum vehicle speed.

There are almost no obstacles to reception of GPS satellite transmissions at an airport construction site, but it must be considered that terrestrial refraction could affect high-accuracy positioning.

The refractive index (n) of air for frequencies less than 30 GHz is shown in Eq. 2:

$$n-1=\left(0.776\frac{P}{T}+3.73\times10^{3}\frac{e}{T^{2}}\right)\times10^{-6} \quad (2)$$

Where P,e: atmospheric pressure and partial pressure of vapor expressed in Pa (1 mbar = 10^2 Pa)

T: temperature in K (0°C = 273K)

Differentiating Eq. 2 by the height, h, gives:

$$\frac{dn}{dh}=\frac{10^{-6}}{T}\left\{0.776\left(\frac{dP}{dh}-\frac{P}{T}\bullet\frac{dT}{dh}\right)+3.73\times10^{3}\frac{1}{T}\left(\frac{de}{dh}-\frac{2e}{T}\bullet\frac{dT}{dh}\right)\right\} \quad (3)$$

According to Eq. 3 and the formula for atmospheric density, readings from a satellite at an elevation of 15° or more are required to obtain locational accuracy of better than 1 cm.

Actual use of the new method at an airport construction site has clarified the following:

(1) This method does not require the services of an expert surveyor to obtain the required level of accuracy. Any lay operator can easily and quickly carry out survey work.

(2) This method requires only a single operator for its operation, so it will eventually lead to great savings in labor costs compared with conventional systems that require a group of at least three to four surveyors.

(3) This method allows a single operator to complete a survey of one hectare in five to six minutes, a task which previously took a team of three to four surveyors an hour.

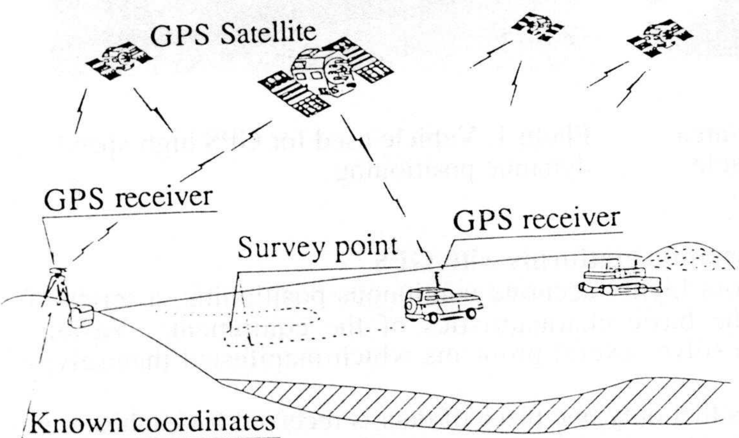

Figure 5. GPS high-speed 3-D topographic survey

4.2 The artificial island project for Kansai International Airport

The high-speed dynamic surveying method described in this paper was put to practical use at the 11th work section of this airport construction site. It was used to survey the height of the fill top over an area of about 21 ha. Before surveying began, the fixed and moving points of the GPS receiver were set at known coordinates. Transmissions were received for a few minutes to determine the number of carrier phases. Then, as shown in Fig. 5, the roving receiver was placed on the roof of a vehicle, which was subsequently driven over unknown points and data taken continuously at intervals of 0.5 to 2.0 seconds.

A total of 5,200 and 1,300 points, respectively, were recorded on the fill top (about 21 ha) and loaded fill (about 9 ha) in a total period of about 3 hours, as shown in Fig. 6. This work at Kansai International Airport quantitatively proved the energy and labor saving effects of this newly developed high-speed dynamic positioning method.

The main features of this new method are summarized below.

(1) A high degree of accuracy, to about 15 mm, is possible, as confirmed in the precision experiments, regardless of the velocity of the vehicle.

(2) The method is especially effective in the planar surveying of a large area.

(3) A single operator is able to complete the topographic surveying of a vast area of land.

(4) The reception interval can be freely chosen according to the purpose of the survey.

(5) Computer processing enables continuous output of analyzed data and coordinates.

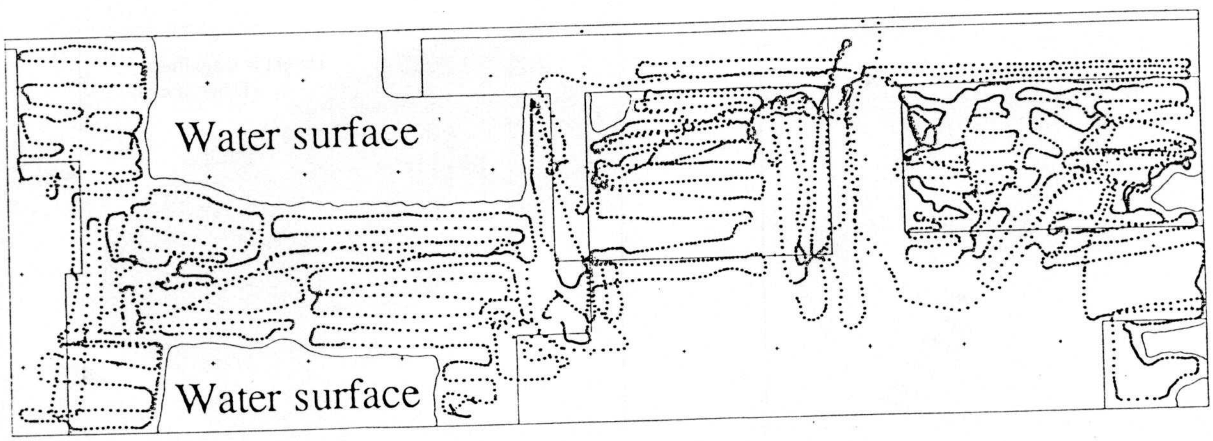

Figure 6. Tracks of survey points (Kansai International Airport: 1,350 x 420 m)

5. SURVEY ROBOT FOR GOLF GREEN CONTOUR MEASUREMENT

A high-accuracy, continuous surveying system using a remote-controlled vehicle, as shown in Photo 2, was used to survey the contours of a golf green. The work entailed equipping a remote control vehicle with a GPS receiving antenna and carrying out a continuous three-dimensional topographical survey of the greens. The system was put into practice at an actual golf course.

This survey enabled contours and bird's-eye views of the golf course to be produced, as shown in Figs. 7 and 8.

This survey robot will enable a data base of well-known golf courses to be created, even allowing them to be duplicated. This function will make it easy to repair existing greens or recover their original form.

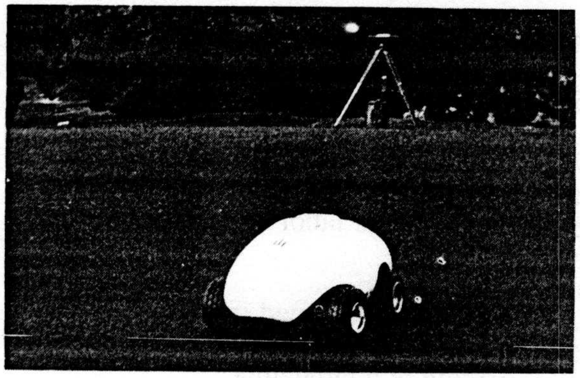

Photo 2. Survey robot

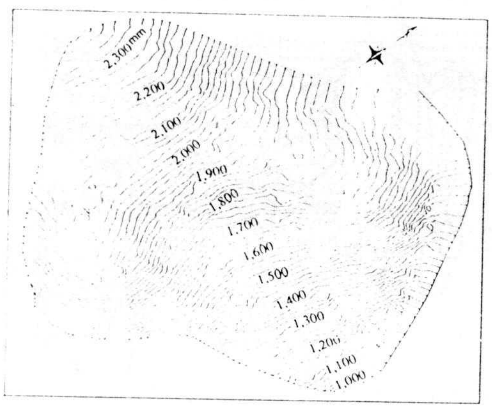

Figure 7. Contours

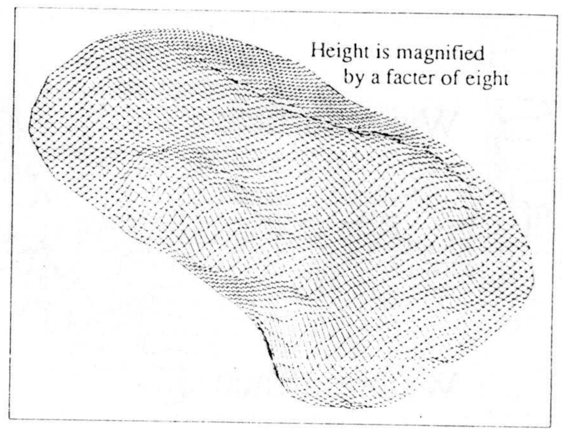

Figure 8. CAD representation in 3-D

6. CONCLUSION

GPS technology is now attracting greater and greater attention from various industries all over the world. Great efforts have been made to widen its range of applications and many of these are now bearing fruit; the system is currently coming into use in a broader range of fields. Practical applications in Japan have also been increasing in number over the past few years. At the same time, Japan's construction industry is moving more and more toward the application of technology in large-scale projects.

The authors' aim was to develop a technique, as proposed in this paper, which would push forward construction technology by using GPS. They hope that this paper will be of use to other researchers and engineers engaged in the same line of work.