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Investigation of a Precise Positioning System for Earth-moving and Construction Machines

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Abstract: The paper discusses a precise positioning model for earth-moving and construction machines (ECM) based on differential correction techniques. The proposed algorithm incorporates both a least squares approach and an iterative method. An opportunity of system implementation is illustrated by the case of an iron ore mine in Kazakhstan, including the selection of the base station and repeater locations.

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1. Introduction

At first glance, precise positioning of earth-moving and construction machines may seem like a straightforward task. However, due to ionospheric and tropospheric errors, the problem becomes non-linear, leading to significant positioning inaccuracies. For ECMs operating in open-pit mines and for surveyors, centimeter-level precision is required, with differential correction methods being employed [1]. A dedicated base station (or multiple) is installed alongside the mine at a location with known coordinates. The correction data from this station is then incorporated into the navigation solution for precise positioning of ECMs. To ensure real-time high-precision positioning of ECMs, a math model based on fundamental principles is considered [2].

Precise positioning of ECMs for the system to be investigated is carried out by applying the specialized satellite receivers designed to measure both the signal propagation time from multiple satellites to the receiver and the signal phase at a carrier frequency. The receiver based on a unidirectional measurement method is implemented. Multiple receivers installed on closely located ECMs can operate simultaneously, each receiver measuring signals independently.

Higher precision is provided by multiple receivers obtaining the same signal from each visible satellite with differences in phase. If any receiver is placed stationarily at a location with known coordinates, positioning of the remaining ones can be performed relative to this stationary receiver with an accuracy of up to several millimeters [3].

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2. Material and methods

Pseudorange (code-based) measurements are characterized by the ability of a receiver to directly determine the signal propagation time based on knowledge of the signal transmission time and the determination of the signal reception time [4]. Multiplying signal propagation time by the signal propagation speed, i.e. the speed of light, yields the desired unambiguous pseudorange value. To obtain the geometric distance between the satellite and receiver, appropriate corrections are applied to the recorded pseudorange value. Since code signals are transmitted from the satellite through a carrier wave modulation, they are characterized by a group propagation speed. This factor must be taken into consideration when determining the time delays of radio signals as they propagate through a dispersive medium such as the ionosphere.

Based on the fundamental equations of pseudorange and actual range in satellite navigation [5] further analysis is conducted:

- the pseudorange equation for the i-th satellite differs from the actual range by an error term (satellite clock error, receiver clock error, signal propagation deviation etc):

$$P_i = \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2} + D, i$$

$$P_i = \overline{1, M} \quad (1)$$

- the corresponding actual range equation is given as follows:

$$R_i = \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2} \quad (2)$$

To determine coordinates, at least four satellites are required, yielding a system of four equations with four unknowns. Since this system is nonlinear due to the fact that the error (D) is unique for each satellite, the least squareы method is applied [6]. The least squareы objective function is formulated as follows:

$$F = \sum_{i=1}^{M} f_i^2 = \sum_{i=1}^{M} (R_i + D - P_i)^2 \to min \quad (3)$$

To find the minimum, first derivative is taken with respect to each variable, yielding:

$$\begin{cases} 2\sum_{i=1}^{M}(R_i + D - P_i)\frac{1}{R_i}(x - x_i) = 0 \\ 2\sum_{i=1}^{M}(R_i + D - P_i)\frac{1}{R_i}(y - y_i) = 0 \\ 2\sum_{i=1}^{M}(R_i + D - P_i)\frac{1}{R_i}(z - z_i) = 0 \\ \sum_{i=1}^{M}(R_i + D - P_i)\frac{1}{R_i} = 0 \end{cases} \quad (4)$$

Further, a system of nonlinear algebraic equations, comprising four equations for a single satellite is considered. For solving the system an initial approximation is defined, and the equations are expanded in Taylor series around the chosen initial approximation, yielding the following:

$$\sum_{i=1}^{M}(R_i(x^k, y^k, z^k, D^k) + D - P_i)(x^k - x_i) + \sum_{i=1}^{M}(\frac{1}{2R_i(x^k, y^k, z^k, D^k)} 2(x^k - x_i)(x^k - x_i) + (R_i(x^k, y^k, z^k, D^k) + D - P_i))\Delta x + \sum_{i=1}^{M}(\frac{1}{2R_i(x^k, y^k, z^k, D^k)} 2(y^k - y_i)(x^k - x_i)\Delta y + \sum_{i=1}^{M}(\frac{1}{2R_i(x^k, y^k, z^k, D^k)} 2(z^k - z_i)(x^k - x_i)\Delta z + \sum_{i=1}^{M}(\frac{1}{2R_i(x^k, y^k, z^k, D^k)}\Delta D = 0 \quad (5)$$

$$\sum_{i=1}^{M}(R_i(x^k, y^k, z^k, D^k) + D - P_i)(y^k - y_i) + \sum_{i=1}^{M}(\frac{1}{2R_i(x^k, y^k, z^k, D^k)} 2(x^k - x_i)(y^k - y_i)\Delta x + \sum_{i=1}^{M}(\frac{1}{2R_i(x^k, y^k, z^k, D^k)} 2(y^k - y_i)(y^k - y_i) + (R_i(x^k, y^k, z^k, D^k) + D - P_i))\Delta y + \sum_{i=1}^{M}(\frac{1}{2R_i(x^k, y^k, z^k, D^k)} 2(z^k - z_i)(y^k - y_i)\Delta z + \sum_{i=1}^{M}\frac{(y^k - y_i)}{2R_i(x^k, y^k, z^k, D^k)}\Delta D = 0 \quad (6)$$

$$\sum_{i=0}^{M}(R_i(x^k, y^k, z^k, D^k) + D - P_i)(z^k - z_i) + \sum_{i=0}^{M}(\frac{1}{2R_i(x^k, y^k, z^k, D^k)} 2(x^k - x_i)(z^k - z_i)\Delta x + \sum_{i=0}^{M}(\frac{1}{2R_i(x^k, y^k, z^k, D^k)} 2(y^k - y_i)(z^k - z_i)\Delta y + \sum_{i=0}^{M}\left(\frac{1}{2R_i(x^k, y^k, z^k, D^k)} 2(z^k - z_i)(z^k - z_i) + (R_i(x^k, y^k, z^k, D^k) + D - P_i)\right)\Delta z + \sum_{i=0}^{M}\frac{(z^k - z_i)}{2R_i(x^k, y^k, z^k, D^k)}\Delta D = 0 \quad (7)$$

$$\sum_{i=1}^{M}(R_i(x^k, y^k, z^k, D^k) + D - P_i) + \sum_{i=1}^{M}(\frac{1}{2R_i(x^k, y^k, z^k, D^k)} 2(x^k - x_i)\Delta x + (\frac{1}{2R_i(x^k, y^k, z^k, D^k)} 2(y^k - y_i)\Delta y + \sum_{i=1}^{M}(\frac{1}{2R_i(x^k, y^k, z^k, D^k)} 2(z^k - z_i)\Delta z + \sum_{i=0}^{M}\frac{(z^k - z_i)}{2R_i(x^k, y^k, z^k, D^k)}\Delta D = 0, \quad (8)$$

where "k" denotes the approximation index, and Δx, Δy, and Δz represent differences between the coordinate values from the previous and current iterations of the system's solution.

To simplify the system of equations, matrix form is employed, namely:

$$\begin{bmatrix} a_{1,1} & a_{1,2} & a_{1,3} & a_{1,4} \\ a_{2,1} & a_{2,2} & a_{2,3} & a_{2,4} \\ a_{3,1} & a_{3,2} & a_{3,3} & a_{3,4} \\ a_{4,1} & a_{4,2} & a_{4,3} & a_{4,4} \end{bmatrix} \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \\ \Delta D \end{bmatrix} = \begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{bmatrix}, \quad (9)$$

where:

$$a_{1,1} = \sum_{i=1}^{M}(R_i(x^k, y^k, z^k, D^k) + D - P_i)(x^k - x_i) + \sum_{i=1}^{M}(\frac{1}{2R_i(x^k, y^k, z^k, D^k)} 2(x^k - x_i)(x^k - x_i) + (R_i(x^k, y^k, z^k, D^k) + D - P_i));$$

$$a_{1,2} = \sum_{i=1}^{M}(\frac{1}{2R_i(x^k, y^k, z^k, D^k)} 2(x^k - x_i)(x^k - x_i);$$

$$a_{1,3} = \sum_{i=1}^{M}(\frac{1}{2R_i(x^k, y^k, z^k, D^k)} 2(z^k - z_i)(x^k - x_i);$$

$$a_{1,4} = \frac{(x^k - x_i)}{2R_i(x^k, y^k, z^k, D^k)};$$

$$a_{2,1} = \sum_{i=1}^{M}(\frac{1}{2R_i(x^k, y^k, z^k, D^k)} 2(x^k - x_i)(y^k - y_i);$$

$$a_{2,2} = \sum_{i=1}^{M}(\frac{1}{2R_i(x^k, y^k, z^k, D^k)} 2(y^k - y_i)(y^k - y_i) + (R_i(x^k, y^k, z^k, D^k) + D - P_i));$$

$$a_{2,3} = \sum_{i=1}^{M}(\frac{1}{2R_i(x^k, y^k, z^k, D^k)} 2(z^k - z_i)(y^k - y_i);$$

etc.,

$$b_1 = \sum_{i=1}^{M}(R_i(x^k, y^k, z^k, D^k) + D - P_i)(x^k - x_i);$$

$$b_2 = \sum_{i=1}^{M}(R_i(x^k, y^k, z^k, D^k) + D - P_i)(y^k - y_i);$$

$$b_3 = \sum_{i=1}^{M}(R_i(x^k, y^k, z^k, D^k) + D - P_i)(z^k - z_i);$$

$$b_4 = \sum_{i=1}^{M}(R_i(x^k, y^k, z^k, D^k) + D - P_i);$$

The solution of the system is performed by an iterative method via successive approximations until the deltas become less than 0.001.

The algorithm is as follows: an initial approximation is set, then the elements of matrix A and vector b are calculated, and finally the next approximation is determined.

$$x^{k+1} = x^k + \Delta x; \quad (10)$$

$$y^{k+1} = y^k + \Delta y; \quad (11)$$

$$z^{k+1} = z^k + \Delta z; \quad (12)$$

$$D^{k+1} = D^k + \Delta D. \quad (13)$$

3. Results and discussion

Based on the conducted mathematical modelling, a feasibility of precise positioning system implementation for earth-moving and construction machines is illustrated by the case of an iron ore mine in Kazakhstan.

In the light of current study, a site alongside an iron ore mine must be selected and a continuously operating base station must be installed onsite to perform differential correction. This stage is essential for the comprehensive implementation of automation in the operation of ECM and other users. An installation of a base station will substantially enhance both the precision and timeliness of determining ECM's position in real time. The continuously operating base station will collect both code and phase data from satellite navigation systems and transmit data to the receivers of ECMs and other users.

Moreover, the existing local coordinate system at the iron ore mine should be taken into account, which has previously served as the basis for large-scale surveys of the quarry at various scales. The shape of the iron ore quarry at the surface is roughly circular with a diameter of 3 km and depth of 700 meters.

Taking into account the terrain and the existing buildings and structures adjacent to the iron ore quarry, to establish the high-precision positioning system, comprising three primary network stations for ECM is expedient, with one station being the base. This number of network stations is considered to be sufficient for both the establishment and subsequent operation of the positioning system over an area of approximately 7.6 square kilometers at the iron ore quarry.

Further, the station layout is examined in detail. The base station should be located at the only viable option - the existing ore management building. This placement is optimal, as the ore management building is the only site within the quarry that is secured continuously (24/7). In addition to providing security, this location will reduce costs associated with the installation and operation of the sensitive and expensive equipment within the base station. The second and third network stations should be placed at the existing points of the local geodetic network within the iron ore quarry. Furthermore, all three stations should be positioned at a considerable distance from one another and, preferably, at approximately equal intervals, since satellite navigation measurements rely on a network adjustment method for the precise determination of coordinates [7]. Accordingly, the second and third stations should be placed at two points of the local geodetic network within the iron ore quarry, as shown in Figure 1.

All three stations satisfy the requirements for satellite geodetic network stations, as each offers an unobstructed view of the sky for satellite reception.

In Fig. 1, the base station of the precise positioning system for ECM is represented by a small triangle, the two remaining network stations are denoted by squares, and the existing points of the local geodetic network within the iron ore quarry are indicated by circles.

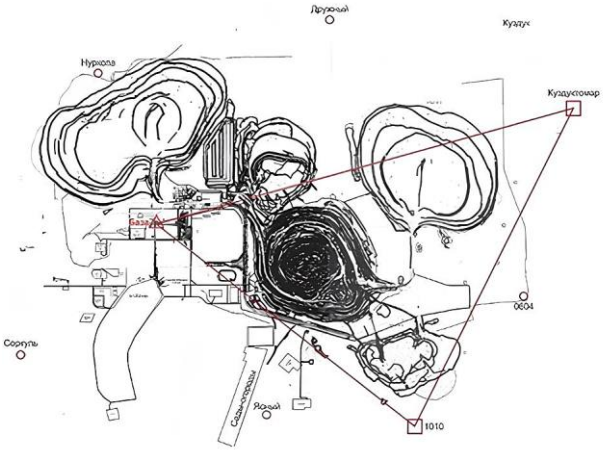


Fig. 1. Placement of network stations.

Mounting the base station tower on the ore management building complies fully with the recommendations [8, 9]. The ore management building is a reinforced concrete structure built more than 15 years ago. No visible signs of foundation damage or wall cracks are observed in the building. It's worth mentioning that the ore management building is ideally located, being suited at a considerable distance from both the quarry blasting sites and the railway tracks.

Within the ore management building itself, when installing the base station, a number of requirements should also be taken into account. To reduce measurement errors in pseudoranges caused by noise in the base station receiver's signal path, antenna cable length must be minimized. The receiving antenna must be positioned in an area free from obstructions for clear satellite signal reception and must be installed at an elevation of more than 10° above the horizon—for instance, on the building's roof. At the same time, convenient access to the antenna for operation and maintenance should be ensured. Based on these requirements, mounting the antenna on the load-bearing wall of the ore management building is proposed, taking into account the placement of the satellite receiving equipment, as shown in Fig. 2.

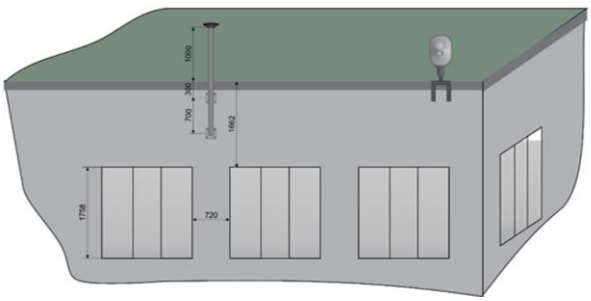


Fig. 2. Mounting the base station on the ore management building.

However, the ore management building is located at a considerable distance from the edge of the quarry, and the same applies to the two other network stations. Moreover, to maintain continuous communication with ECMs at the lower part of the quarry and to refine the differential

correction signals they receive, a repeater at the quarry's edge should be installed to retransmit these signals. The repeater may be placed on the dispatch building situated at the quarry's edge [10]. Frequent blasting operations at the iron ore quarry forbid installation of the base station's navigation unit alongside the quarry's edge, as the resultant soil vibrations significantly disrupt the relative determination of the phase center's coordinates in the receiving antenna at the ground station. The existing antenna mast of the dispatch building is considered optimal for installing the repeater, as it facilitates high-precision satellite measurements on the slopes and floor of the iron ore quarry and ensures the transmission of differential corrections via signals retransmitted by GSM and VHF repeater antennas from the quarry's edge.

When placing the repeater at the edge of the quarry, the repeater's receiving antenna must be oriented toward the dispatch tower by tilting it. A secondary radio communication zone should be provided by the transmitting antenna. Additionally, the repeater must be installed at an elevated position if it is located at a considerable distance from the dispatch tower, as shown in Fig. 3.

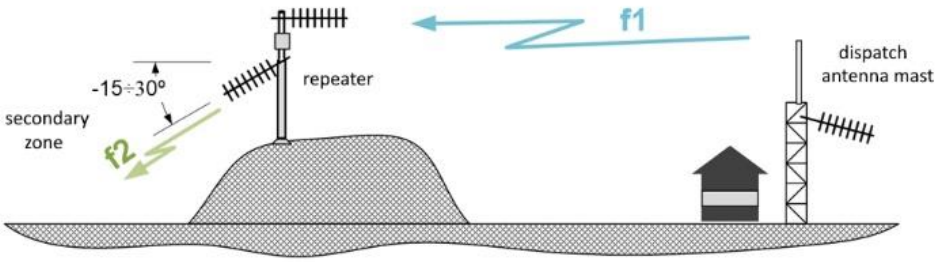


Fig. 3. Orientation of the repeater antennas when installed on spoil heaps.

When installing the repeater at the edge of the iron ore quarry, the antennas should be set with an inclination of approximately +30° (for frequency f1) and –30° (for frequency f2), respectively. (Fig. 4).

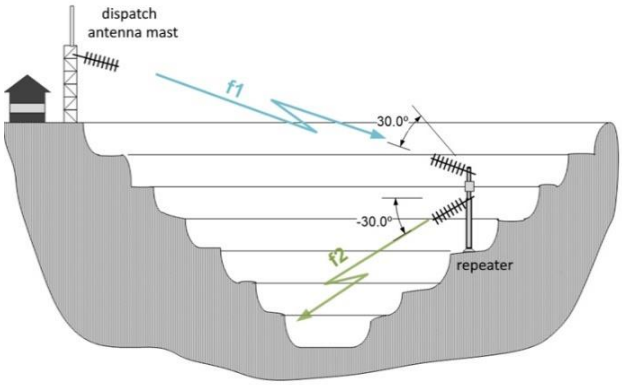


Fig. 4. Orientation of the repeater antennas when installed within the quarry.

4. Conclusion

The results of mathematical modlling demonstrate the feasibility of developing an effective and precise positioning system for ECMs based on differential correction. The proposed system will enhance both the accuracy and timeliness of ECM control, thereby increasing productivity and operational safety.

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