Introduction potential of GPS navigation technology for supervision control at capital construction, reconstruction and conversion projects

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Abstract. This article analyzes potential use of various navigation technologies to implement building supervision functions for capital construction, reconstruction and conversion projects. It indicates the basic prerequisites for the development of such technologies and describes the navigation physical principle applicable due to its properties for a certain range of supervision functions in the construction industry. The article also examines testing of corresponding software systems on the construction sites in Moscow in control operations by the Technical Customer’s engineers, and analyzes the potential of using adjacent navigation systems for similar purposes as compared with the main physical and technical characteristics of implementation in professional software packages.

1 Introduction

The following is the definition of the systems science that now offers additional possibilities of developing human activities in a number of areas including the construction industry. Navigation (Latin *navigatio*, from Latin *navigo* – ‘I go by boat’) is a field of study that focuses on methods to determine velocity, location and orientation of moving objects; it has evolved as a result of the general ship navigation study development (Table 1). In the modern world, it is virtually impossible to imagine human life without the navigation technology - navigation systems enable safe cargo and passenger transportation by air, sea and land; coordination of space devices and rescue operations; meeting the requirement of online tracking in large cities and heavy urban traffic, etc [1-2].

Table 1. Milestones of navigation science development.

Item No.	Historical period	Location	Event
1.	Ancient World (6th century B.C.)	Ancient Greece	The properties of magnetic iron ore are described by Thales of Miletus for the first time ever
2.	Middle Ages (11th century; ~	China, Song dynasty	In his work ‘The Four Great Chinese Inventions’ Joseph Nidem, researcher of Chinese and ancient

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	1044)		Chinese science, mentions among other inventions (paper, gunpowder, book printing) the first magnetic device determining an object's location (i.e. compass) to facilitate navigation along with maps and pilot charts used in sea voyages.
3.	Middle Ages (12th - 13th century)	Europe	First prototypes of the modern compass. In the late 12th century Necame of England and Gio de Provins of France were the first to describe the simplest boussole ("compass" in French), a device intended to determine the magnetic azimuth.
4.	Middle Ages (early 14th century)	Europe (Italy)	Flavio Fioia of Italy refined on the existing magnetic device (i.e. compass, 16 rhumbs)
5.	Renaissance (16th century)	Europe	The compass card was divided into 32 rhumbs, and the needle framing was put inside a gimbal to remove the impact of ship motions
6.	Modern Age (17th century)	Europe	The compass was equipped with a direction finder, i.e. a rotating diametric ruler with sighting devices at the ends with its center based on the box cover above the needle
7.	Contemporary history (1908)	Europe (Germany)	Hermann Anschütz-Kaampfe, a German engineer, invented the gyroscope
8.	Contemporary history (1920)	Europe	Plus Fours Routefinder, the first prototype of the modern navigator in the form of a wrist watch
9.	Contemporary history (1930)	Europe	Iter-Auto, the first in-car navigator
10.	Contemporary history (1966)	USA	The first electronic navigation system with the punched cards technology developed by General Motors (Driver Aid Information and Routing)
11.	Contemporary history (1957)	USSR	Launching of first artificial satellite of the Earth marked the start of the satellite navigation era.
12.	Contemporary history (1974 - 1994)	USA	In 1974, the idea of satellite navigation based on the Doppler Effect was implemented by the US military which launched the first of the 24 GPS satellites to cover the entire area of the Earth. The last of them was launched in 1994. There are 32 satellites of that kind at the moment.
13.	Contemporary history (since 1976)	USSR	Development of the GLONASS project was officially started in the USSR in 1976, but the first two satellites however were not launched until 1984. Similarly to GPS, 24 satellites are required to cover the entire area of the Earth,
14.	Contemporary history (since 1983)	USA, USSR	In 1983, following the Soviet Air Force shoot down a Korean Airline civil aircraft that incurred into the Soviet Union airspace, it was decided to create GPS for civil needs.

2 Methods

The Satellite Navigation System (Tables 2 and 3) is an integrated system consisting of equipment placed in space orbit and on the ground and designed to determine the coordinates and trajectory parameters of an object. There is a group of satellites in space orbit with each of them emitting signals in the radiofrequency band [3-4]. Once the signal reaches an object on Earth and is processed, the distance from the object to the satellite is calculated using previously known data (such the location of the satellite). The distance is determined by calculating the formulas of wave propagation in the medium. The waves from the satellites propagate at the speed of light, and the lag between their emission in the space and receipt on Earth is directly proportional to the distance between the object and the satellite [5-6].

Table 2. Types of modern navigation systems.

Item No.	Navigation system type	System subtypes groups
1.	Satellite-borne	NAVSTAR (GPS); GLONASSS; Doris etc.
2.	Radio-navigational	Based on extremely low frequency waves, medium frequency waves, high frequency waves, etc.
3.	Inertial	Platform INS, platformless INS

Table 3. Satellite navigation systems over the periods.

Item No.	Developer country	Name of the satellite navigation system	Brief description based on the main parameters	Historical period
1.	USA	Transit	The system included 5 satellites in polar orbits and was originally intended to periodically offset the guidance systems of sea-based ballistic missiles, as well as to correct the errors of ship inertial navigation systems under any weather conditions. The objects location error is approx. 25 m, location determination period is 1–3 hours, and location determination time is 10–16 minute. The TRANSIT system has developed into GPS	1958 – 1996
2.	USSR	Cyclone	The world’s first combined navigation & communication satellite complex. A satellite-borne transponder was fitted for wireless communication. With a group of 6 Parus satellites in orbit, the system was able to determine plane coordinates accurate to 80–100 meters.	1967 – 1978
3.	USSR (RF)	Tsikada	The system included 4 navigation satellites at an incline of 83 degrees with uniform distribution of orbital plane along the equator.	1979 – 1997
4.	USSR (RF)	Parus	The systems were used to provide space communications and navigation	1976 – 2010

			data for submarines and surface vessels of the Russian Navy. They form the Cyclone Space Military Navigation & Communication System. The satellites are put into subpolar orbits at an incline of 82.9 degrees, perigee altitude of 970 km and apogee altitude of 1,200 km.	
5.	USA	NAVSTAR (GPS)	<p>The development of the US Department of Defense. The GPS system provides services on a global scale. The orbital group initially consisted of 24 satellites located in 6 orbital planes with an inclination of 64.5 degrees to the geostationary orbit plane. Satellite signals have the following carrier frequencies: L1=1575.42 MHz, L2=1227.60 MHz, L5=1176.45 MHz (the latest models). The operating GPS wavelength falls within UHF, which means that the signal reception level may be severely degraded by physical obstacles and magnetic storms. This factor constitutes the main problem in precise determination of an object's location. However, the accuracy may be increased using signal phase measurement.</p> <p>The satellite's data transmission frequency is 1575.42 MHz. The data include: ephemeris – precise orbit and clock adjustment data for each satellite; almanac – location data of the satellite.</p> <p>There are 31 GPS satellites currently in orbit. Each satellite transmits its unique signature consisting of random sequence (Pseudo Random Noise (PRN) code) of 1,023 units of 0's and 1's.</p> <p>There are 2 types of PRN code: a P-code processed by a GPS receiver with an accuracy of more than 10 m; and a C/A-code with an accuracy of approx. 20 m. The unique ID is added in the code to determine the signal-transmitting satellite and to measure the signal transit time.</p>	
6.	USSR (RF)	GLONASS	<p>The GLONASS satellites are situated in the medium-altitude circular orbit at an altitude of 19,400 km with inclination of 64.8 degrees and orbital period of 11 hours and 15 minutes. These satellites continuously emit two types of navigation signals: a standard accuracy navigation signal in L1 band</p>	

			(1.6 GHz), and a high accuracy navigation signal in L1 and L2 bands (1.2 GHz). The system exploits frequency division of channels - each satellite generates a wave at its own carrier frequency. The GLONASS system exploits a differential movement model. It means determining the satellite coordinates at a given point in time requires a solution to a system of differential equations using numerical integration.	
7.	France	Doris	Designed to meet geodesic and geophysical requirements	
8.	EU (European Union)	GALILEO	Provides a unique global Search and Rescue (SAR) service with an essential feedback function	
9.	China	Beidou	Beidou operates in a test mode and offers positioning, navigation and time determination services for China and “some of its surrounding regions.”	
10.	Japan	Quasi-Zenit	The satellite segment includes 3 satellites in total. Their orbits will be chosen to ensure that their sub-satellite points trace out identical trajectories on the surface with identical time intervals. At least one satellite will always be visible at an angular altitude of over 70 degrees in Japan and Korea.	

The principle of satellite signal generation in the NAVSTAR (GPS) system is as follows: the necessary synchronizing pulses and frequencies are generated as derivatives of the resonant frequency of atomic clock. The pulses are generated by the generators of the carrier frequency at which the satellite signals are transmitted, as well as by the PRN code generator and data generator (Fig. 2) [7-8].

Due to large distances and limited power of the signal that the satellite is capable to generate, information is transmitted digitally as a binary code (bit stream) rather than as an analog signal. Accordingly, the initial analog signal is preliminarily digitized and then converted by modulation into a radio signal with a certain frequency range capable of being received by on-ground devices (due to problems in recognizing LF signals, including background noise). This operation results in the frequency translation of digital signal into the HF range. This allows transceivers to ensure recognition of the required signal from the satellite at a certain frequency [9-10]. Thus, the modulation “lays” the information (digital signal) onto the L1 carrier frequency of a satellite (Table 3) – the information from the satellite is initially modulated by the C/A code (Table 3), then BPSK (binary phase-shift keying) performs modulation by a discrete signal of the L1 carrier frequency, at which the signal can be received by the devices (Figure 3 and 4).

Fig. 1. NAVSTAR GPS logo.

Fig. 2. Simplified block diagram of the satellite signal generation principle.

Fig. 3. GPS satellite data structure.

Fig. 4. Flow chart of analog signal conversion into a signal available for receivers.

To determine the object's coordinates, it is necessary to calculate the transit time for four satellites $\Delta t_1, \Delta t_2, \Delta t_3, \Delta t_4$. Distance from the satellite to the object is called the R-

range. At a given satellite location $X_{Sat}Y_{Sat}Z_{Sat}$, the R-range is calculated for each satellite using the transit time [11-12].

Fig. 5. 3D coordinate system.

Let us assume that a user's clock is not synchronized with UTC (Coordinated Universal Time). Therefore, additional error Δt_0 appears. The result of error allowance for the actual range is called the pseudo-range PSR.

$$\Delta t_{measured} = \Delta t + \Delta t_0 \tag{1}$$

$$PSR = \Delta t_{measured} \cdot c = (\Delta t_1 + \Delta t_0) \cdot c \tag{2}$$

$$PSR = R + \Delta t_0 \cdot c \tag{3}$$

Where: R is the actual range from satellite to user; c is the speed of light; $\Delta t_1 R$ is the signal transit range from satellite to user; Δt_0 is the difference between satellite's and user's clock; PSR is the pseudo-range [13-14].

The actual range in the Cartesian coordinate system:

$$R = \sqrt{(X_{Sat} - X_{User})^2 + (Y_{Sat} - Y_{User})^2 + (Z_{Sat} - Z_{User})^2} \tag{4}$$

Therefore, the pseudo-range is calculated using the formula:

$$PSR = \sqrt{(X_{Sat} - X_{User})^2 + (Y_{Sat} - Y_{User})^2 + (Z_{Sat} - Z_{User})^2} + \Delta t_0 \cdot c \tag{5}$$

To determine the four unknown variables ($\Delta t_0, X_{User}, Y_{User}, Z_{User}$), four independent equations are required.

The following equation holds good for 4 satellites ($i= 1...4$)

$$PSR_i = \sqrt{(X_{Sat_i} - X_{User})^2 + (Y_{Sat_i} - Y_{User})^2 + (Z_{Sat_i} - Z_{User})^2} + \Delta t_0 \cdot c \tag{6}$$

3 Results

The following factors comprise the general error in the system: 10 ns time error of the satellite clock, error in the satellite orbit position, heterogeneity of propagation medium. The table reflects the effect of errors on data accuracy [15-16].

Table 4. Measurement error factors.

Item No.	Factor	Error, m
1.	Ionosphere effect	4
2.	Satellite clock	2.1
3.	Receiver measurements	0.5
4.	Ephemeris data	2.1
5.	Troposphere effect	0.7
6.	Multi-directivity	1.4
7.	General RMS value (non-filtered)	5.3
8.	General RMS value (filtered)	5.1
9.	Vertical error (1 sigma (68,3%)VDOP=2,5)	12.8
10.	Vertical error (2 sigma (95,5%)VDOP=2,5)	25.6
11.	Horizontal error (1 sigma (68,3%)HDOP=2,5)	10.2
12.	Horizontal error (2 sigma (95,5%)HDOP=2,5)	20.4

Originally intended for military purposes only, GPS is used today for civilian applications such as surveillance, navigation (air, sea, and ground), positioning, speed measurement, time detection, control of stationary and moving objects, and so on. The system operator guarantees the standard civil consumer the following accuracy (Tables 5, 6) for 95% of the time:

Table 5. Accuracy of GPS.

Item No.	GPS Accuracy Type	Value in appropriate units
1.	Horizontal accuracy	≤ 13 m
2.	Vertical accuracy	≤ 22 m
3.	Time accuracy	~ 40 ns

Table 6. Comparative analysis of the two main existing satellite systems.

Item No.	GPS NAVSTAR vs GLONASS		
	Parameter	GPS	GLONASS
1.	Signal and its structure	Code division of signals	Frequency division of signals
2.	Satellites movement description	Osculating elements model	Differential movement model
3.	Construction geometry of satellites	6 orbital planes, 32 satellites	3 orbital planes, 24 satellites
4.	Accuracy	5 m	2.5-2.8 m

Despite the worldwide use of the GPS navigation system in various fields of science and technology (including the global construction industry), Analytical Table 6 shows that Russia’s GLONASS system has a number of technical advantages resulting in better accuracy of both plane and high-altitude positioning. However, it is the worldwide coverage of GPS that makes it the most popular navigation equipment and software solution. As for the construction industry, let us review the main areas of application of a

navigation system in tackling applied engineering, transport, management and qualimetry tasks (Table 7).

Table 7. Practical application of navigation in the field of construction supervision and site survey.

Item No.	Application area	Implementation effectiveness exemplified by a specific task solution
1.	Construction machinery	Reduction of construction fleet hijacking rate (particularly truck mixers, self-propelled cranes, bulldozers, front loaders and excavators) by means of specialized GPS trackers
2.	Construction machinery	Construction fleet route tracking (which also means fuel consumption control) and working time control by means of specialized GPS trackers
3.	Road and airfield construction	Roadway condition survey; roadway composition control; road paving monitoring; maintenance vehicles work optimization; shunting management optimization
4.	Construction of engineering infrastructure	High-precision laying of linear infrastructure (e.g. laying, inspection and monitoring of utility networks and systems)
5.	Inspection of buildings, structures and other facilities	Measurement work; monitoring of buildings and structures using the navigation field of global navigation satellite systems (GNSS)
6.	Inspection of buildings, structures and other facilities	Local flaw detection of construction objects, including generation of defect lists
7.	Construction supervision and operation of the Technical Customer services	In-process quality control of construction products. Quality control of finished construction products. Verification of the on-site construction and installation work progress (factual completion, in some cases – work progress in numerical form). Control service engineer work optimization and automation. Generation of a defect database for a facility.
8.	Geodesic support of construction and inspection of buildings and structures	Geodetic work using appropriate technologies; in-field positioning and object snapping; satellite geodesy methods in high-rise buildings construction
9.	Construction and installation works at industrial and civil construction projects	Earthworks quality and volume control using machinery fitted with satellite signal receivers (e.g. bulldozers with 3D leveling system); relative movement control
10.	Cadastral work	Measurement work
11.	Construction of underground mass transit facilities	Geodesic and surveying work
12.	Bridge construction	Relative movement control

Geodesic methods based on satellite navigation are widely used in building supervision. They ensure a high accuracy, while on-line in-field positioning accelerates field work because there is no need to provide any extra geodetic control networks which involve reference points transfer. Based on the principles of global navigation satellite systems (GNSS), integrated software systems are being developed for the qualimetric needs of control procedures in the construction and inspection of existing buildings and structures; such systems include defect detection systems with a positioning function on extended objects (Fig. 6) and technical condition monitoring using GNSS.

Integrated construction supervision using GNSS may include the following operations:

- Construction expertise

- Quality, volume and cost inspection of construction and installation works
- Pre-design inspection of projects and land plots
- Executive documentation control
- Designer's field supervision
- Recording of the actual state of facilities and construction site
- Work completion time monitoring
- Pre-insurance and insurance inspection of facilities
- Certification of buildings and structures
- Facilities inspection in evaluation operations
- etc.

Fig. 6. Opportunities of placing defect tags and other comments on the plan of a relevant drawing when conducting building supervision of a facility using the integrated engineering software of Construction Inspection and Technical Supervision (with a function of downloading information to mobile devices and computers).

4 Conclusions

Despite available high-precision advanced technologies, there are a number of difficulties related to establishing the maximum measurement accuracy in the matters of global satellite support in tackling engineering problems. Satellite navigation systems alone (neither GPS nor GLONASS, which is in fact more accurate) are incapable of providing sufficient accuracy for construction needs due to a number of specific physical and technical features (including those previously discussed in this article). For this reason there is a need for indirect geodetic instruments to ensure more accurate positioning. The use of satellite navigation basics in geodesy has significantly expanded the range of verification capabilities in construction control and monitoring of the technical condition of buildings and structures, from monitoring fluctuations in high-rise buildings to verifying the progress of construction and installation work at the stage of delivery of completed construction products by the General Contractor.

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