Global navigation systems for mobile robots

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Abstract—The article deals with global navigation satellite systems in mobile robotics. The attention is devoted to experimental property evaluation of miniature GPS receivers suitable for navigation of outdoor mobile robots. Modern GPS receivers are characterized by small size, weight, energy consumption and relatively high precision of measured position. The aim is to determine the error of measured position of two GPS sensors. The precision identification is done in defined local coordinate frame on the base of position data gathered throughout three experiments. The procedure used to transform measured position data from WGS84 to the local coordinate system is given. The high precision GPS receiver Leica GPS1200 was used as the reference system.

Keywords—Mobile robot navigation, GPS receiver, WGS 84, Leica GPS1200.

I. INTRODUCTION

AUTONOMOUS mobile robots are capable of motion in the environment and decision making upon information collected by observation of the environment [1], [2]. Navigation of a mobile robot in an unknown and uncertain environment requires knowledge of the robot’s position. Without such knowledge, the robot is unable to perform other tasks and thus it cannot be considered mobile or intelligent. There are many localization methods. The methods range from simple ones, such as odometry, to fairly mathematically rich ones, such as Markov localization. Generally, in a mobile robotics they can be divided in absolute localization methods and relative localization methods [3], [4]. Relative methods are referenced to surrounding objects and they mostly express displacement between two consequent positions. Absolute methods use a global reference frame, which defines a global coordinate system. The approach which uses GNSS (Global Navigation Satellite System) is an example of absolute localisation method suitable for mobile robot localization in outdoor environment.

In order to navigate robot in the outdoor environment, there is a need to integrate the local (relative) and global (absolute) localization approaches. Such data fusion can be effectively realised in local coordinate system, thus the GNSS data has to be transformed to this local frame. Therefore this paper evaluates available GNSS receivers appropriate as position sensors for small scale outdoor mobile robot in local coordinate frame.

The paper is organized as follows. Section 2 describes the basic principles of the GNSS. Section 3 deals with global reference frame used in GPS. Section 4 contains the basic principle of the position data transformation. Section 5 describes the used GPS receivers and the evaluation of the experimental results is presented in Section 6.

II. GLOBAL NAVIGATION SATELLITE SYSTEMS

Global Navigation Satellite System (GNSS) is term used for Earth's artificial satellite system intended for precise measurement of the position and time on whole Earth [5]. Methods used to measure the position by GNSS are based on precise measurement of time and trilateration. The position is given by intersection point of minimum of three spherical surfaces, whose radius is equal to the distance between visible satellite and a measured position. Calculation of the three coordinates (latitude, longitude, and sea level) requires the fourth satellite, which is used for a precise time synchronization (Fig. 1). The more satellites are used for position calculation, the more precise estimate of position should be.

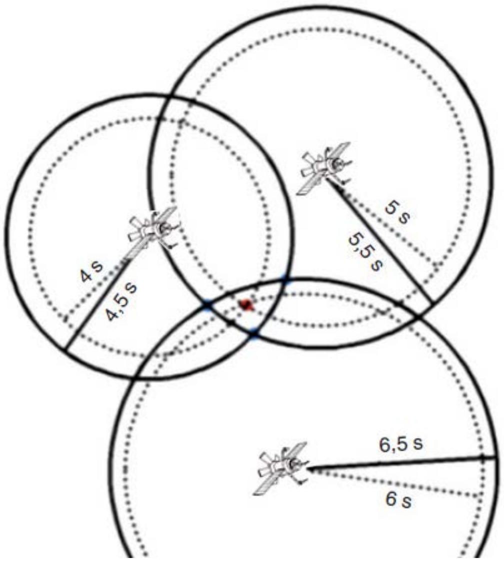

Fig. 1 calculation of the position using three satellites and the impact of time synchronization on this calculation

Currently are two GNSS systems in commission: Navstar GPS (GPS; Global Positioning System) [6] and Glonass [7]. The most commonly used system is GPS. The GPS system comprises of a cosmic, control and a user segments. The user segment includes so called GPS receivers. In principle, GNSS's are not affected by meteorological conditions. However, calculating the position using GPS is somewhat problematic and the position accuracy is affected by many sources of errors.

The most significant are:

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- satellite geometry (the position of the satellites in relation to each other and to he receiver),
- atmospheric effects (delays of signals passing through individual layers of atmosphere),
- multipath effect (signals bounce off solid objects),
- relativistic effects.

The negative impact of the position measurement errors called for proposal of multiple hardware and software solutions for improvement of the measurement accuracy. One approach is to use more precise measuring units such as: INS-GPS (Inertial Navigation System [8]; up to 1 m accuracy), DGPS (Differential GPS [9]; up to 5 m accuracy; in case of the best implementations 10cm), WAAS/EGNOS (Wide Area Augmentation System/Euro Geostationary Navigation Overlay Service [10]; up to 3 m accuracy) and RTK GPS (Real Time Kinematics [11], [12]; up to several centimeters accuracy).

Another way to improve the estimate of the position by GPS receiver is to use some mathematical approaches. To improve precision and accuracy of GPS positioning, many researchers use filters, such as Kalman filter [11], [13], [14], [15], [16], [17] or statistical methods, such as Monte Carlo [18]. Some of them cannot be used in real-time, because they have high computational requirements. Usually, they are used as post-processing methods for data correction.

III. WORLD GEODETIC SYSTEM 1984

The GPS data is referred to unified global coordinate system named World Geodetic System 1984 (WGS 84). The WGS 84 geodetic system comprises of a standard spheroidal reference surface (reference ellipsoid) and a gravitational equipotential surface (the geoid). The reference ellipsoid defines a standard coordinate frame for the Earth. The geoid defines the nominal sea level.

The coordinate origin of the WGS 84 coordinate system is the Earth' centre of mass. The meridian of zero longitude is an International Reference Meridian (IRM), which is defined by the International Earth Rotation and Reference Systems Service (IERS). The Z-Axis is defined by the direction of the IERS Reference Pole (IRP). The X-Axis is defined by the intersection of the IRM and the plane passing through the origin and normal to the Z-axis. The Y-Axis completes a right-handed, Earth-Centered Earth-Fixed (ECEF) orthogonal coordinate system, measured in the equator plane, 90° east of the X-axis [19] and it is graphically depicted in the Fig. 2.

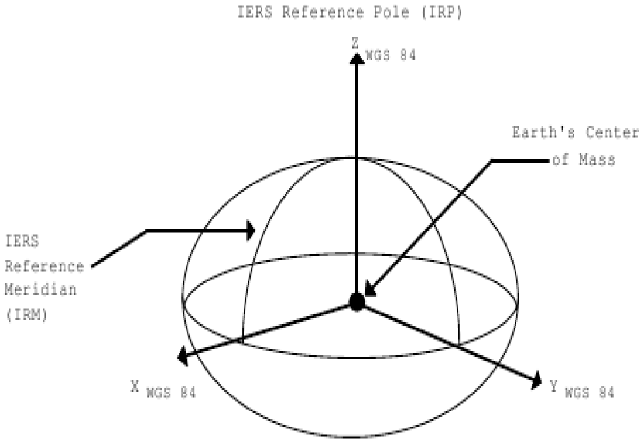

Fig. 2 the WGS 84 coordinate system definition [19]

The shape of the Earth is not spherical, but it is an ellipsoid, slightly flattened at the poles and slightly bulging at the equator. The World Geodetic System (WGS) represents an ellipsoid of which placement, orientation, and dimensions best fit the Earth's equipotential surface coinciding with the geoid. The WGS 84 reference ellipsoid is defined by the four defining parameters: semi-major axis (*a*), flattening (*f*), angular velocity of the Earth (*ω*) and Earth's gravitational constant (*GM*). The defining parameters values are listed in Table 1 [19].

Table 1 WGS 84 four defining parameters [19].

Parameter	Notation	Value
Semi-major Axis	a	6378137 m
Reciprocal value of Flattening	$1/f$	298.257223563
Angular Velocity of the Earth	ω	7292115×10^{-11} rad s^{-1}
Earth's Gravitational Constant	GM	$3986004.418 \times 10^{8}$ m^{3} s^{-2}

For our purposes it will be sufficient to consider geometric parameters only. Mathematically, a reference ellipsoid is an oblate spheroid with two different axes: an equatorial radius (the semi-major axis *a*), and a polar radius (the semi-minor axis *b*). The relation between two axes *a* and *b* is given by following formula:

$$f = \frac{a-b}{a} . \tag{1}$$

The numerical value of the the semi-minor axis for the WGS

84 reference ellipsoid is b = 6356752.3142 m [18].

IV. THE POSITION DATA TRANSFORMATION

The control system of the robot utilizes a local navigational map. Accordingly it is necessary to transform the GPS navigational data to the local navigational map. The proposed procedure transforms the position data from the WGS 84 coordinate system to the local coordinate system (LCS). The relation between the global WGS coordinate system and local coordinate system is depicted in the Fig. 3.

The LCS has the form of two dimensional Cartesian coordinate system in the Euclidean plane. This plane is defined as the tangent plane to the surface of the reference ellipsoid at the chosen point which also serves as the origin of the local coordinate system (Fig. 3).

The first step in the transformation of the GPS coordinate data, it is necessary to select the origin of the local coordinate system appropriately according to the given data set. The point named *O* with the coordinates of the mean value of the WGS spherical coordinates (φ, λ) of the measured points *P* was chosen as the convenient origin. Its coordinates are given as follows:

$$O_{(\varphi,\lambda)} = \left(\sum_{1}^{N} \left(P_{\varphi}\right) \Big/ N , \sum_{1}^{N} \left(P_{\lambda}\right) \Big/ N \right), \tag{2}$$

where *N* is number of waypoints, φ is the geodetical latitude and λ is the geodetical longitude.

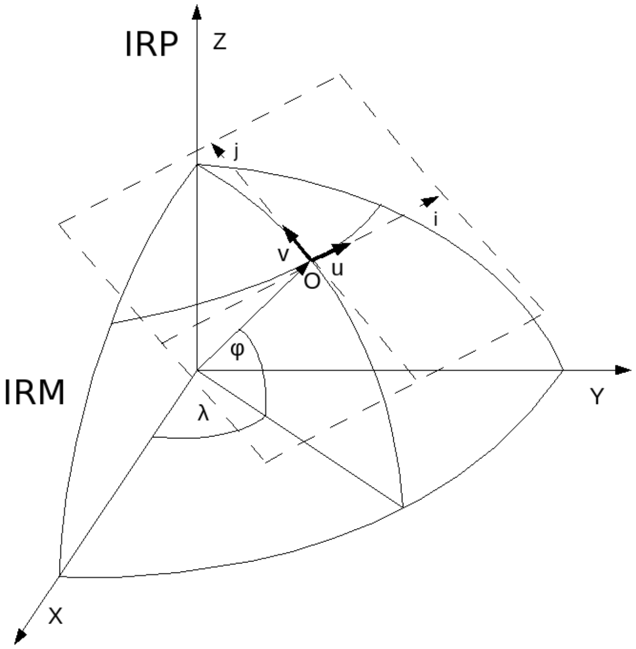

Fig. 3 the WGS 84 coordinate system and the local coordinate system LCS

Now it is necessary to computate the three dimensional geocentric rectangular coordinates (*x*, *y*, *z*) of the origin of the local system in regard to WGS 84. The equations for the coordinates calculation are given as follows [19]:

$$x = \left(N + h\right)\cos\varphi\cos\lambda\,, \tag{3}$$

$$y = \left(N + h\right)\cos\varphi\sin\lambda\,, \tag{4}$$

$$z = \left(\left(b^2 / a^2\right)N + h\right)\sin\varphi\,, \tag{5}$$

where *a* is semi-major axis and *b* is the semi-minor axis of the reference ellipsoid, the *h* denotes the geodetic height (height relative to the ellipsoid), *N* denotes the radius of curvature in the prime vertical. It is defined by the equation:

$$N = \frac{a}{\sqrt{1 - e^2 \sin^2\varphi}}\,, \tag{6}$$

where e^2 denotes the square of the first ellipsoidal eccentricity, which can be computed by the following equation:

$$e^2 = \frac{a^2 - b^2}{a^2}\,. \tag{7}$$

It is also one of the WGS 84 ellipsoid derived geometric constants with value $e^2 = 6.69437999014 \times 10^{-3}$ [19].

After definition of the local coordinate system origin, the second step is to define the equation of the LCS plane in rectangular geocentric coordinates. The general expression of the plane is given as follows:

$$Ax + By + Cz + D = 0\,, \tag{8}$$

where the constants *A*, *B*, *C* are the coordinates of the *normal vector* of the plane. As the LCS plane is also the tangent plane of the reference ellipsoid, the vector (*A*, *B*, *C*) is perpendicular to surface of the ellipsoid in the origin of the local coordinate system *O*. So the normal vector of the plane can be computed as the gradient of the ellipsoid at the point *O*. The mathematical expression of the WGS 84 reference ellipsoid (oblate spheroid) in the Cartesian coordinate system is given by equation:

$$F\left(x,y,z\right):\quad \frac{x^2}{a^2} + \frac{y^2}{a^2} + \frac{z^2}{b^2} = 1\,, \tag{9}$$

where *a* is semi-major axis and *b* is the semi-minor axis of the reference ellipsoid. The gradient of the ellipsoid is given:

$$\nabla F\left(x,y,z\right) = \left(\frac{2\mathrm{x}}{a^2}, \frac{2\mathrm{y}}{a^2}, \frac{2\mathrm{z}}{b^2}\right). \tag{10}$$

Finally the equation of the LCS plane is given as follows:

$$\frac{O_x x}{a^2}+\frac{O_y y}{a^2}+\frac{O_z z}{b^2}=1\,. \tag{11}$$

The third step is to define the right-handed orthonormal Cartesian coordinate system in the LCS plane. So it is necessary in the LCS plane to define two reciprocally perpendicular vectors *u*, *v* of the length of 1 (m) at the LCS origin *O*. First there are two points defined at the ellipsoid surface with the positions exactly at east and north directions in regard of origin *O* as follows:

$$U_G(\varphi,\lambda)=\left(O_\varphi, O_\lambda + c\right), \tag{12}$$

$$V_G(\varphi,\lambda)=\left(O_\varphi + c, O_\lambda\right). \tag{13}$$

The constant *c* is optional angular distance of the suitable scale. The value of $c = 0.1$ was determined as sufficient. By the application of the equations 3, 4, and 5 the WGS 84 Cartesian coordinates (U_{Gx}, U_{Gy}, U_{Gz}) and (V_{Gx}, V_{Gy}, V_{Gz}) of the points U_G and V_G are calculated. It is essential to compute the projection of these two points U_G and V_G to the LCS plane. The two lines l_u and l_v perpendicular to system plane passing through the points U_G and V_G are defined. The parametric expressions of the lines l_u and l_v with the directional vector (*A*, *B*, *C*) passing through points U_G and V_G is given as follows, for $t \in R$:

$$l_u(t): \begin{array}{l} x = U_{Gx} + At \\ y = U_{Gy} + Bt \\ z = U_{Gz} + Ct \end{array}, \tag{14}$$

$$l_v(t): \begin{array}{l} x = V_{Gx} + At \\ y = V_{Gy} + Bt \\ z = V_{Gz} + Ct \end{array}. \tag{15}$$

It is necessary to compute the intersection points of the lines l_u and l_v with the LCS plane. We denote these intersects as U_L and V_L. The vectors defined by these points and the origin *O* determinate the directions of the positive half–axes of the coordinate system in the LCS plane. To obtain unit vectors, the normalization of these vectors is required. The orthonormal basis vectors *u* and *v* of the LCS in regard to the WGS 84 are now given by following equations:

$$u(x,y,z)=\frac{U_L - O}{\left|U_L - O\right|}, \tag{16}$$

$$v(x,y,z)=\frac{V_L - O}{\left|V_L - O\right|}, \tag{17}$$

where |*x*| denotes the length of the vector *x*. These two vectors *u* and *v* defines the transition from one coordinate system to another and the local coordinate system is completely defined.

Now it is possible to proceed to the last step of the points coordinates transformation process. It is necessary to perform the same procedure as in case of the calculation of the vectors *u* and *v*. For each point *P* in input data set, by the application of the equations 3, 4, 5, the WGS 84 Cartesian coordinates (P_x, P_y, P_z) are calculated. The calculation of the coordinates of the perpendicular projections of these points to the LCS then follows. The parametric equation of the line perpendicular to the LCS and passing through the point *P* for the parameter $t \in R$ is given as follows:

$$l_p(t): \begin{array}{l} x = P_x + At \\ y = P_y + Bt \\ z = P_z + Ct \end{array}, \tag{18}$$

The coordinates of the point P_L, given by the intersection of the LCS plane and the line l_p are calculated by application of the formulas 8 and 18. Finally the vector *p* is computed by the application of the following equation:

$$p(x,y,z)=P_L - O\,. \tag{19}$$

To determine the LCS 2D coordinates of the point P_L lying in the LCS plane, it is necessary to find the expression of the vector *p*, through the linear combination of the basis vectors *u* and *v*. The vector *p* can be expressed by means of *u* and *v*:

$$p(x,y,z)=\alpha u(x,y,z)+\beta v(x,y,z)\,. \tag{20}$$

The local 2D coordinates of the P_L point are directly given by the computation of the coefficients α and β:

$$p(i,j)=(\alpha,\beta)\,. \tag{21}$$

This procedure is gradually applied to all points of the input data set.

V. GPS RECEIVERS

The essential parameters of GPS receivers intended for a small scale outdoor mobile robot are in addition to precision of the measured position dimensions, weight and energy consumption [20]. In the class of small receivers, the energy consumption is sufficiently low, so the weigh and size determined selection of sensors. For the evaluation of appropriate GPS receiver for small outdoor mobile robot, the following GPS receivers were used: SparkFun Electronics Venus GPS-11058 evaluation board, [21] and GlobalTop Tech Inc. FGPMMOPA6B [22]. As the reference GPS system the Leica Geosystems GPS1200 was used [23].

A.Protocol NMEA 0183

GPS and its wide expansion represents the huge source of data. However, there can be problem when the data from GPS receiver are transformed to the program for evaluating the measurements, which is not compatible with this receiver. Therefore, protocols were developed for communication with GPS receivers: NMEA 0183, RTCM SC-04 and RINEX [24]. The most widely used protocol is NMEA 0183 [25].

Protocol NMEA 0183 describes the electronic and data aspect of the communication between naval electronics and between GPS receivers. It uses simple serial communication protocol based on ASCII characters. Data transfer is divided into sentences. These sentences contain the basic data about the position, but they can also include additional information, such as a number of visible satellites or strength of signal. Each sentence has its own identifier, through which is recognized the meaning of values in the body of sentence:

- sentence begins with character $,
- next 5 characters identify the type of sentence,
- comma separates each data,
- sentence ends with character *,
- after the character *, two digits checksum follows (XOR of ASCII characters).

The most frequently used sentences in NMEA 0183 protocol are:

- RMC (recommended minimum, which is used by most GPS devices),
- GGA (Global Positionin System Fix Data),
- GSA and GSV hold information about the list of visible satellites and the strength of signals.

B.Reference GPS receiver Leica GPS1200

As a reference frame high precision GPS receiver a Leica GX1230+GNSS /ATX1230+GNSS was used (Fig.4). This receiver is able to receive GPS L1, L2 and L5 frequencies, Glonass L1 and L2 frequencies and Galileo E1, E5a, E5b, E5ab and E6 frequencies. Moreover, this receiver is able to perform both code and phase measurements with DGPS or RTK corrections. Because of these facts Leica GX1230+ is able to achieve 0.2 mm positioning precision at phase measurements on L1 and L2 frequencies and 2 cm positioning precision at code measurements on L1 and L2 frequencies. This receiver has been designed primarily for geodetic measurements. However, its parameters make it suitable for many applications including absolute outdoor mobile robot localization. On the other hand this application is limited with its high price, weight and energy consumption.

Fig. 4 the reference GPS receiver Leica GPS1200

C.Tested GPS receivers

The GPS receivers Venus GPS-11058 (Fig.4) and FGMMOPA6B (Fig.5) with their small size parameters are intended for variable applications where the very small size and weight of the sensor is required.

The compact sensor Venus GPS-11058 is based on SkyTraq Technology Venus 638FLPx chip. It is a 65 channel receiver working on GPS frequency L1 with active or passive antenna. Its size is 29.2mm x 17.8mm x 6.24mm (SMA connector) and it has 3.3V DC main power input with consumption of 90 mA at full power and 60mA at reduced power operation mode. It has maximal position accuracy 2.5m Circular Error Probability (CEP) [21].

The FGMMOPA6B is a patch on top 66 channel GPS receiver based on MediaTek MT3329 chip working on L1 frequency. Its dimensions are 16mm x 16mm x 6mm with dimensions of patch antenna of 15mm x 15mm x 4mm and it has weight of 6g. Its main power input is 3.3 V with consumption of 37 mA. Its 2D-RMS position accuracy is 3m and its maximal accuracy with DGPS is 2.5m [22].

Fig. 5 the Venus GPS-11058 GPS receiver

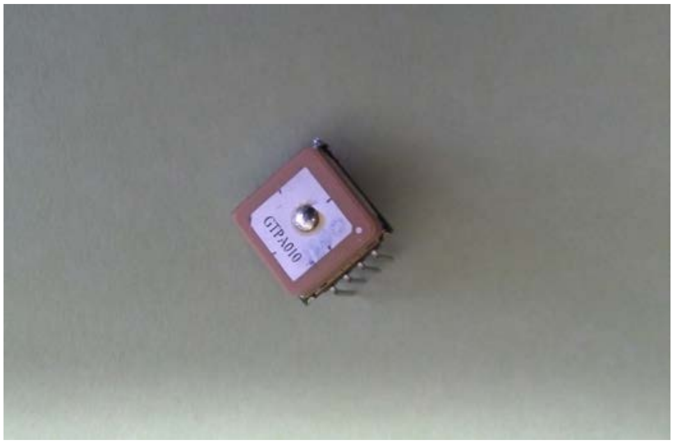

Fig. 6 the FGMMOPA6B GPS receiver

The receivers have serial data output in the form of NMEA 0183 protocol sentences based on WGS84 datum [24].

VI.EXPERIMENTAL RESULTS

The experiments were performed at three different places with various satellite visibility conditions. The receivers were mounted on experimental platform in such arrangement with their receiving antenas being close to each other. The experimental places were chosen with aim to maximally approximate the real conditions during outdoor robot navigation. The first experimental position was situated in greater vicinity of quite tall building and thus it allows receive the signal from relatively great space. The experimental setup of the first experiment is visible in Fig. 7. The second experimental place was located in the middle of large open place where the maximum number of the satellites can be received. The third experimental position was situated under the wall of the mentioned building and thus the sky was greatly shadowed.

Fig. 7 experimental setup

Three data sets with all three GPS receivers were measured at these places and overall nine data sets were obtained. The data from reference Leica GPS1200 system were used to define the origin of the local coordinate system. The measured positions from evaluated small scale receivers were then transformed into local coordinate system in order to compare their accuracy on the unified basis. Each data set contained unequal but sufficient number of measurements to evaluate the precision of the receiver and it was statistically evaluated. The number of visible GPS satellites was recorded during each experiment in order to check their influence on the accuracy of receivers. The parameters of interest were the mean value of measured position data transformed to local coordinate system and mean Euclidean distance of measured data from origin of local system. The processed experimental data are summarized in Table 2 and Table 3.

Table 2 experimental results of evaluation of the GPS-11058 GPS receiver

Experiment	**Number of visible GPS satellites**	**GPS-11058**	
		(x, y) [m]	**d [m]**
1	7	2.79, -12.28	12.59
2	8	-1.90, 10.79	10.95
3	4	-1.40, 21.52	21.56

Table 3 experimental results of evaluation of the

FGMMOPA6B GPS receiver

Experiment	Number of visible GPS satellites	FGMMOPA6B	
		(x, y) [m]	d [m]
1	7	-4.12, -10.10	10.91
2	8	-0.93, 7.65	7.71
3	4	-10.72, -3.05	11.14

The measured data transformed to the local coordinate system for the case of second measurement with FGMMOPA6B GPS receiver (the most precise measured position) is shown in Fig.8. The position data for measured position with greatest error is shown in Fig. 9. The measured positions are depicted as small dots.

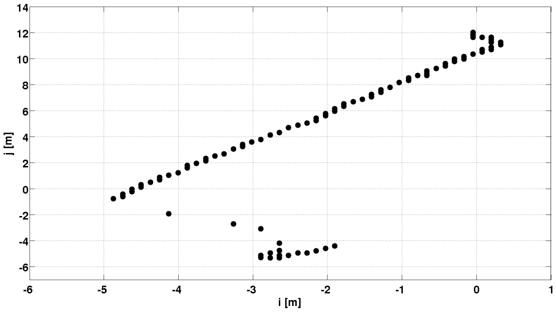

Fig. 8 data of the most precise measured position

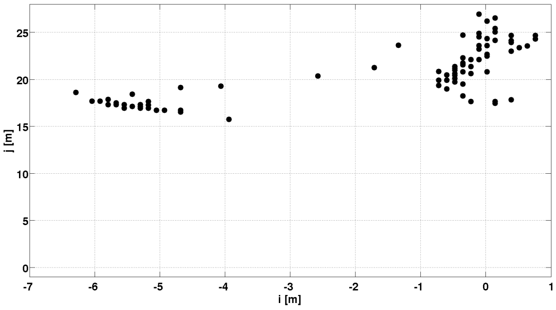

Fig. 9 data of the measured position with greatest error

VII.CONCLUSION

The aim of the performed experiments was to evaluate appropriate GPS receivers for a small scale outdoor mobile robot. The chosen GPS systems had a very small size and weight and the task was to identify their real position accuracy in conditions close to outdoor navigation of mobile robots. The evaluation was performed in the local coordinate frame with equal error measurements. The values in the Table 2 and 3 showed the assumed dependency of position correctness on the number of visible satellites. Thus the reliability of the robot localization procedures based on the use of GNSS data might fluctuate during the navigation in the environment. In accomplished experiments the FGMMOPA6B GPS receiver measured the real positions a slightly more accurately than GPS-11058. This fact can be likely given by the used GPS receiver chip. On the other hand, the accuracy of the measured position changed during the measurement from approximately 5m to 10m (Fig.6). Such considerable change is even greater in comparison with the difference of measured accuracies of the receivers and it can be caused by change of the satellites configuration. Thus the reliable comparison of the GPS receivers requires to gather the data from much more measurements within longer time periods. Another interesting result of the experiment was, that most of the measured data was considerably asymmetrically shifted from the real position only along one axis of the local coordinate system. Along the second axis they were located more symmetrically. Even though, the performed experiments revealed interesting properties of the used GPS receivers and opened new ideas for further work.

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