

SYSTEM AND METHOD FOR POSITIONING AND NAVIGATION OF AN OBJECT

TECHNOLOGICAL FIELD

The present invention relates to positioning and navigating techniques, and more particularly to a technique for determining location data of an object carrying a receiver on board, which receives signals from transmitters.

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BACKGROUND

Determining location and respective spatial coordinates of static or moving objects is important in various applications, which provide navigation and location-based service to a user.

10 Conventional techniques, such as global positioning systems (GPS), are known for providing data indicative of location of an object. GPS services can also be used for providing spatial coordinates of the object, so as to navigate the user to a desired destination. A typical GPS setup may include a GPS receiver, that can, for example, be integrated in a hand-held electronic device or mounted on a vehicle, and corresponding
15 software communicating with the GPS receiver. The software is configured to receive data on the location of the user associated with the GPS receiver, and to process these data in order to direct the user to a desired location.

Operation of GPS systems is based on relative position of the GPS specialized satellites, and on time data provided from accurate and synchronized clocks associated
20 with the GPS receiver and the corresponding GPS specialized satellites. Each such satellite continuously transmits a radio signal (carrier wave with appropriate modulation) containing time and location data indicative of its position. The GPS receiver utilizes these data to determine its precise position.

GENERAL DESCRIPTION

Although conventional GPS based techniques are currently widely used, these techniques suffer from evident drawbacks related to limited accuracy in determining position of the GPS receiver. These accuracy issues arise since the ionosphere and the troposphere can slow down the rate of signal propagation. Weather conditions and electromagnetic interference can also affect data transmission. These drawbacks may impose severe difficulties on attaining accurate measurements of an object, especially when such measurements involve high-velocity variations of the receiver's position, e.g. when the receiver is mounted on a drone.

Furthermore, conventional GPS techniques suffer from vulnerability to deception which may be caused by intentional signal jamming or signal blocking, stemming from the fact that GPS systems operate using predetermined RF frequencies utilized by GPS satellites. Additionally, when GPS signals arrive to the Earth's surface (where GPS receivers are typically located), they can be relatively weak, and the GPS receivers' sensitivity can be insufficient for accurate detection.

Thus, there is still a need in the art for, and it would be useful to have, a novel positioning and navigating technique providing accurate information on distance and position data of an object.

It would be advantageous to have a positioning system and method that operates independently of any external satellites, such as GPS satellites, thereby enhancing accuracy of the system.

It would also be advantageous to have a positioning system and method enabling determination of accurate position as well as kinematic data, e.g., velocity and acceleration of an object that moves at high-velocities.

It would be useful to have a further improvement of a positioning system so that it would be robust with respect to signal jamming and blocking, thereby enabling improved performance and operation of the system in hostile environments.

The present invention partially eliminates the deficiencies of existing GPS systems, and provides a novel positioning system and method for determining location data of an object. Generally, the location data may include spatial coordinates (e.g., Cartesian or any other coordinates) of the object.

According to an embodiment of the present invention, the system includes one or more transmitting units. Each transmitting unit is configured to transmit a multi-

frequency signal. More specifically, each transmitting unit transmits a multi-frequency pulsed signal which includes at least two different signal frequency components. In this connection, the system of the present invention operates with a discrete set of signal frequency components which are selected by the user/operator of the system and therefore
5 are not restricted by frequencies utilized in conventional GPS systems. Such a configuration enables operation in hostile environments in which signal jamming or signal blocking may impose difficulties for operation of the system.

The positioning system also includes a receiver system mounted on the object. The receiver system is configured and operable to receive multi-frequency signals
10 provided by the transmitting units, and to determine phases of each signal frequency component of the multi-frequency signals.

The positioning system further includes a processing system which is in data communication with the receiver system. The processing system is configured to receive the phases of each signal frequency component of the multi-frequency signals, and to
15 determine a distance D between the transmitting units and the object. The processing system can also be adapted for determining the location data of the object.

According to some embodiments of the present invention, the location data include K parameters defining a set of desired location parameters and a time parameter of the object. Specifically, the desired parameters include location coordinates $x(t)$, $y(t)$
20 and $z(t)$ of the object at time t , and a system time T parameter. Accordingly, K can be selected from 1, 2, 3 and 4, depending on the number of the parameters which are desired to determine. In order to determine the desired number K of the parameters, the system should include K transmitting units. According to some embodiments of the present invention, the multi-frequency signal includes a sum of number L of signal frequency
25 component f_i , where i is the number index of the signal frequency component. Preferably, but not mandatory, the signal frequency components f_i are mutually prime numbers, namely the only integer that divides both of them is 1.

According to some embodiments of the present invention, the receiver is configured to receive multi-frequency signals provided by the transmitting units, to
30 analyze the multi-frequency signals and to determine number L of the signal frequency components f_i of each multi-frequency signal.

According to an embodiment of the present invention, the receiver system includes a time clock unit coupled to phase measuring unit for activation of measurements

of the phases ϕ_i with a predetermined measurement rate (i.e., time interval of measurements) T_s . The measurements of the phases ϕ_i can be carried out with a predetermined measurement rate T_s that can, for example, be in the range of 10 microseconds to 100 microseconds.

5 According to some embodiments of the present invention, the distance D between the transmitting unit and the object is determined by $D = c \Delta t$, where c is the light speed, and Δt is the time of propagation of the multi-frequency signals between the transmitting unit and the receiver (mounted on the object).

According to an embodiment of the present invention, the time Δt can be
10 determined from the equation:

$$\Delta t = \frac{\phi_i + 2\pi N_i}{2\pi f_i}$$

where ϕ_i is the phase of an i -th signal frequency component determined by the receiver, and N_i is a number of wave cycles of the i -th signal frequency component spanned on the distance D .

15 According to some embodiments of the present invention, the number i of the signal frequency component f_i is selected from 0, 1, 2 and 3. In this case, the number of the signal frequency components f_i transmitted by the at least one transmitting unit is four, i.e., f_0, f_1, f_2 , and f_3 .

According to some embodiments of the present invention, the processing system
20 is configured for determining the number N_0 of cycles of the first signal frequency component f_0 by using any one of the equations:

$$N_0 = -\frac{f_0\phi_1 - f_1\phi_0 + 2\pi M_0 f_0}{2\pi(f_0 - f_1)}$$

$$N_0 = -\frac{f_0\phi_2 - f_2\phi_0 + 2\pi M_1 f_0}{2\pi(f_0 - f_2)}$$

and

25
$$N_0 = -\frac{f_0\phi_3 - f_3\phi_0 + 2\pi M_2 f_0}{2\pi(f_0 - f_3)},$$

where M_0, M_1 , and M_2 are additives to the number of cycles N_0 for the signal frequency components f_1, f_2 , and f_3 , correspondingly.

According to some embodiments of the present invention, the processing system is configured for determining M_0 and M_1 by using the following algorithm: for each M_0

selected from 0 to $(M_{0\max}-1)$ and for each M_1 selected from 0 to $(M_{1\max}-1)$, the processing system calculates integer numbers corresponding to M_0 and M_1 such that M_0 and M_1 satisfy the following equation:

$$\frac{f_0\phi_1 - f_1\phi_0 + 2\pi M_0 f_0}{f_0 - f_1} = \frac{f_0\phi_2 - f_2\phi_0 + 2\pi M_1 f_0}{f_0 - f_2},$$

- 5 where $M_{0\max} = \text{round}[2\pi(f_1 - f_0)T_s]$ and where $M_{1\max} = \text{round}[2\pi(f_2 - f_1)T_s]$, where T_s is the measurement rate.

According to some embodiments of the present invention, the processing system is further configured for determining M_0 and M_1 by using the equation:

$$\Delta p_{\text{mx}} := \left\lfloor \frac{f_0\phi_1 - f_1\phi_0 + 2\pi \cdot \text{mod}(\text{mx}, \text{Ma0}) \cdot f_0}{2\pi \cdot (f_0 - f_1)} \right\rfloor - \left\lfloor \frac{f_0\phi_2 - f_2\phi_0 + 2\pi \cdot \text{floor}\left(\frac{\text{mx}}{\text{Ma0}}\right) \cdot f_0}{2\pi \cdot (f_0 - f_2)} \right\rfloor$$

- 10 In this case, the numbers M_0 and M_1 are determined by calculating integer numbers that satisfy the condition $\Delta p_{\text{mx}}=0$ for each mx selected from 0 to $(M_{0\max} \cdot M_{1\max}) - 1$, where $M_{0\max} = \text{round}[2\pi(f_1 - f_0)T_s]$ and where $M_{1\max} = \text{round}[2\pi(f_2 - f_1)T_s]$, where T_s is the measurement rate, and $\text{Ma0} = M_{0\max}$ or $M_{1\max}$.

- 15 According to some embodiments of the present invention, the processing system is configured to calculate M_2 by using the equation:

$$\frac{f_0\phi_1 - f_1\phi_0 + 2\pi M_0 f_0}{f_0 - f_1} = \frac{f_0\phi_3 - f_3\phi_0 + 2\pi M_2 f_0}{f_0 - f_3}$$

- According to some embodiments of the present invention the processing system is further configured to determine kinematic data selected from velocity and acceleration of the object. The determination is based on the location data and system time T . For
20 example, the kinematic data can be determined by taking time derivatives from the location data coordinates of the receiver mounted on the object.

- According to some embodiments of the present invention, the processing system is configured to receive the phase data ϕ_i of each signal frequency component for each of the multi-frequency signals from the receiver system and to determine kinematic data
25 based on the phase data ϕ_i .

According to some embodiments of the present invention, the system includes three transmitting units, which are designated by letter symbols a , b and c . Thus, the transmitting units have coordinates (x_a, y_a, z_a) , (x_b, y_b, z_b) and (x_c, y_c, z_c) , correspondingly.

In this case, determination of the location data includes calculating three location coordinates $x(t)$, $y(t)$ and $z(t)$ of the object at time t , correspondingly. Accordingly, the processing system can be configured to determine the three location coordinates $x(t)$, $y(t)$ and $z(t)$ of the object by using the equations:

$$\begin{aligned} D_a &= \sqrt{(x(t) - x_a)^2 + (y(t) - y_a)^2 + (z(t) - z_a)^2} \\ D_b &= \sqrt{(x(t) - x_b)^2 + (y(t) - y_b)^2 + (z(t) - z_b)^2} \\ D_c &= \sqrt{(x(t) - x_c)^2 + (y(t) - y_c)^2 + (z(t) - z_c)^2}, \end{aligned}$$

where D_a , D_b and D_c are distances from the three transmitting units to the receiver system, correspondingly.

According to some embodiments of the present invention, the system includes four transmitting units, which are designated by letter symbols a , b , c and d . The transmitting units have coordinates (x_a, y_a, z_a) , (x_b, y_b, z_b) , (x_c, y_c, z_c) and (x_d, y_d, z_d) , correspondingly.

In this case, the processing system is configured to determine the three location coordinates $x(t)$, $y(t)$ and $z(t)$ of the object and the system time T by solving the following system of equations:

$$\begin{aligned} c(T - \Delta t_a) &= \sqrt{(x(t) - x_a)^2 + (y(t) - y_a)^2 + (z(t) - z_a)^2} \\ c(T - \Delta t_b) &= \sqrt{(x(t) - x_b)^2 + (y(t) - y_b)^2 + (z(t) - z_b)^2} \\ c(T - \Delta t_c) &= \sqrt{(x(t) - x_c)^2 + (y(t) - y_c)^2 + (z(t) - z_c)^2} \\ c(T - \Delta t_d) &= \sqrt{(x(t) - x_d)^2 + (y(t) - y_d)^2 + (z(t) - z_d)^2}, \end{aligned}$$

wherein T is the system time which is common to the four transmitting units and the receiver. In this system of equations, $c(T - \Delta t_a)$, $c(T - \Delta t_b)$, $c(T - \Delta t_c)$ and $c(T - \Delta t_d)$ are the distances between the transmitting unit and the receiver system mounted on the object, correspondingly.

According to another aspect of the present invention, there is provided a positioning method for determining location data of an object. The positioning method utilizes the system described above. The positioning method includes transmitting a multi-frequency signal which includes at least two different frequencies and measuring the phases of each signal frequency component of the multi-frequency signal. The positioning method also includes determining a distance D between the transmitting units and the object, and determining the location data of the object.

There has thus been outlined, rather broadly, the more important features of the invention in order that the detailed description thereof that follows hereinafter may be better understood. Additional details and advantages of the invention will be set forth in the detailed description, and in part will be appreciated from the description, or may be learned
5 by practice of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

In order to better understand the subject matter that is disclosed herein and to exemplify how it may be carried out in practice, embodiments will now be described, by way of non-limiting example only, with reference to the accompanying drawings, in
10 which:

Fig. 1 illustrates a schematic block diagram of a positioning system, according to an embodiment of the present invention;

Fig. 2 illustrates a schematic block diagram of a positioning system, according to another embodiment of the present invention; and

15 **Fig. 3** illustrates a schematic block diagram of a positioning system, according to a further embodiment of the present invention.

DETAILED DESCRIPTION OF EMBODIMENTS

The principles and operation of the positioning system and method for determining location data of an object according to the present invention may be better understood with
20 reference to the drawings and the accompanying description, it being understood that these drawings and examples in the description are given for illustrative purposes only and are not meant to be limiting. The same reference Roman numerals and alphabetic characters will be utilized for identifying those components which are common in the positioning system and its components shown in the drawings throughout the present description of the invention.

25 It should be noted that the blocks in the drawings illustrating various embodiments of the present invention are intended as functional entities only, such that the functional relationships between the entities are shown, rather than any physical connections and/or physical relationships.

Some portions of the detailed descriptions, which follow hereinbelow, are presented
30 in terms of algorithms and/or symbolic representations of operations on data represented as physical quantities within registers and memories of a computer system. An algorithm is

here conceived to be a sequence of steps requiring physical manipulations of physical quantities and leading to a desired result. Usually, although not necessarily, these quantities take the form of electrical or magnetic signals capable of being stored, transferred, combined, compared, and otherwise manipulated. In the present description, these signals
5 can be referred to as values, elements, symbols, terms, numbers, or the like.

Unless specifically stated otherwise, throughout the description, utilizing terms such as "computing" or "calculating" or "determining" or "obtaining" or the like, refer to the action and processes of a computer system, or similar electronic processing device, that manipulates and transforms data.

10 Referring to **Fig. 1**, a schematic block diagram of a positioning system **10** configured for determination of location data of an object **11** is illustrated, according to an embodiment of the present invention. The positioning system **10** includes a transmitting unit **12** and a receiver system **111** mounted on the object **11**. According to this embodiment, the object **11** and the receiver system **111** constitute a unitary body.

15 The positioning system **10** also includes a processing system **13** in data communication with the receiver system **111**. The processing system **13** communicates with the receiver system **111** via a communication network, using any known suitable wired and/or wireless communication techniques and data protocols.

According to an embodiment, the processing system **13** can be integrated with and
20 be a part of the receiver system **111**. Alternatively, the processing system **13** can be a stand-alone unit separate from the receiver system **111**. When desired, the processing system **13** can include a display, printer and/or other monitoring devices (not shown).

In operation, the transmitting unit **12** is located at a certain distance D from the object **11**. Generally, a positioning method for determining the distance D and the location
25 data of the object **11** by using the positioning system **10** includes transmitting a multi-frequency signal comprising at least two different signal frequency components and measuring the phases of each signal frequency component of the multi-frequency signal. Then the processing system **13** calculates distance D between the transmitting unit **12** and the object **11**, and the location data of the object **11**.

30 According to an embodiment, the transmitting unit **12** is configured and operable for transmitting multi-frequency signals having a predetermined number L (at least two) of signal frequency components having frequencies f_i such that all the different signal frequency components are originated at the same time, where i is the number index of the

signal frequency component, $i = 0, 1, \dots, L$. The frequencies f_i are selected from a predetermined set of frequencies.

The multi-frequency signal may be transmitted via the transmitting unit **12** with a certain time pattern, for example, as a sequence of periodic pulses, each pulse having a number L of signal frequency components. Alternatively, the multi-frequency signal may be a continuous signal having a number L of signal frequency components.

Upon arrival of the multi-frequency transmitted signal to the receiver system **111**, each signal frequency component has a certain phase that can be measured. Accordingly, the receiver system **111** is configured and operable to receive the multi-frequency signals including the signal frequency components having frequencies f_i originated from the transmitting unit **12**, and to determine the phase ϕ_i of each signal frequency component of the multi-frequency signal at the time of arrival to the transmitting unit **12**. To this end, the receiver system **111** includes a phase measuring unit **120**, which is adapted to receive the signal frequency components as an input data and to measure the phase ϕ_i of each signal frequency component.

According to some embodiments of the present invention, the receiver system **111** is configured to receive multi-frequency signals provided by the transmitting unit **12**, to analyze the multi-frequency signals and to determine a number L of the signal frequency components f_i of each multi-frequency signal.

According to an embodiment of the present invention, the processing system **13** is in data communication with the receiver system **111**, and is configured to receive the phase data ϕ_i of each signal frequency component of the multi-frequency signal provided by the phase measuring **120** unit, and to calculate the distance D between the transmitting unit **12** and the object **11**.

According to an embodiment of the present invention, the receiver system **111** includes a time clock unit coupled to the phase measuring unit **120** for activation of measurements of the phases ϕ_i with a predetermined measurement rate T_s . The measurements of the phases ϕ_i can be carried out with a predetermined measurement rate T_s , that can, for example, be in the range of 10 microseconds to 100 microseconds.

In operation, upon receiving the phase data ϕ_i of each signal frequency component, the processing system **13** calculates the time of propagation Δt of the multi-

frequency signals from the transmitting unit **12** to the receiver system **111** mounted on the object **11**.

According to an embodiment of the present invention, the time of propagation Δt of the signal frequency components from the transmitting unit **12** to the receiver system **111** is determined by:

$$\Delta t = \frac{\phi_i + 2\pi N_i}{2\pi f_i}, \quad (1)$$

where N_i is the number of wave cycles of an i -th signal frequency component spanned on the distance D between the transmitting unit **12** and the object **11**. This number of cycles is denoted by $N_i = N_0 + M_i$, where N_0 is the number of cycles of the first signal frequency component and M_i is the additive number to the number of cycles N_0 for the i -th signal frequency component.

Generally, the number of cycles N_0 of the first signal frequency component can be calculated by:

$$N_0 = \text{floor} \left(\frac{2\pi f_0 dt - \phi_0}{2\pi} \right). \quad (2)$$

According to an embodiment of the present invention, the multi-frequency signal includes four signal frequency components having frequencies f_0 , f_1 , f_2 , and f_3 . In this case, N_0 which is a number of cycles of the first signal frequency component f_0 can be obtained by using any one of the following equations:

$$N_0 = -\frac{f_0\phi_1 - f_1\phi_0 + 2\pi M_0 f_0}{2\pi(f_0 - f_1)} \quad (3a)$$

$$N_0 = -\frac{f_0\phi_2 - f_2\phi_0 + 2\pi M_1 f_0}{2\pi(f_0 - f_2)} \quad (3b)$$

and

$$N_0 = -\frac{f_0\phi_3 - f_3\phi_0 + 2\pi M_2 f_0}{2\pi(f_0 - f_3)}, \quad (3c)$$

where M_0 , M_1 , and M_2 are additives to the number of cycles N_0 for the signal frequency components having frequencies f_1 , f_2 , and f_3 , correspondingly.

According to an embodiment of the present invention, for determination of the values of the additives M_0 and M_1 , the processing system **13** executes the following algorithm.

The additives M_0 and M_1 are selected from 1 to their corresponding maximum value. Specifically, M_0 is selected from 0 to $(M_{0\max}-1)$, where $M_{0\max} = [2\pi(f_1 - f_0)T_s]$ and M_1 is selected from 0 to $(M_{1\max}-1)$, where $M_{1\max} = [2\pi(f_2 - f_1)T_s]$, where T_s is the measurement rate.

- 5 The processing system **13** calculates integer values of M_0 and M_1 such that M_0 and M_1 satisfy the following equation:

$$\frac{f_0\phi_1 - f_1\phi_0 + 2\pi M_0 f_0}{f_0 - f_1} = \frac{f_0\phi_2 - f_2\phi_0 + 2\pi M_1 f_0}{f_0 - f_2} \quad (4)$$

- According to another embodiment of the present invention, for determination of
10 the values of the additives M_0 and M_1 by the processing system **13**, the following relationship can be used:

$$\Delta p_{\max} := \left\lceil \left\lfloor \frac{f_0\phi_1 - f_1\phi_0 + 2\pi \cdot \text{mod}(mx, Ma0) \cdot f_0}{2\pi \cdot (f_0 - f_1)} \right\rfloor - \left\lfloor \frac{f_0\phi_2 - f_2\phi_0 + 2\pi \cdot \text{floor}\left(\frac{mx}{Ma0}\right) \cdot f_0}{2\pi \cdot (f_0 - f_2)} \right\rfloor \right\rceil. \quad (5)$$

- 15 In this case, the integer values of M_0 and M_1 can be selected so as to satisfy the condition $\Delta p_{\max}=0$. Specifically, mx can be selected from 0 to $(M_{0\max} \cdot M_{1\max}) - 1$, where $M_{0\max} = \text{round}[2\pi(f_1 - f_0)T_s]$ and where $M_{1\max} = \text{round}[2\pi(f_2 - f_1)T_s]$ and T_s is the measurement rate . and $Ma0 = M_{0\max}$ or $M_{1\max}$.

- After determining M_0 and M_1 , the processing system **13** can calculate the additive
20 M_2 , for example, by solving the equation:

$$\frac{f_0\phi_1 - f_1\phi_0 + 2\pi M_0 f_0}{f_0 - f_1} = \frac{f_0\phi_3 - f_3\phi_0 + 2\pi M_2 f_0}{f_0 - f_3} \quad (6)$$

Accordingly, the additive M_2 can be calculated by:

$$M_2 = \frac{f_0 - f_3}{2\pi f_0 (f_0 - f_1)} (f_0\phi_1 - f_1\phi_0 + 2\pi M_0 f_0) - \frac{f_0\phi_3 + f_3\phi_0}{2\pi f_0}. \quad (6a)$$

- After determination of all the additives M_0 , M_1 , and M_2 the processing system **13**
25 can determine N_0 and Δt by using the abovementioned equations (3a)-(3c) and (1), accordingly.

Upon determination of the time of propagation Δt , the processing system **13** can determine the distance D between the transmitting unit **12** and the object **11** by using the equation $D = c \Delta t$, where c is the speed of propagation of the electromagnetic radiation.

The proposed technique has been checked by simulation for the multi-frequency signal including four signal frequency components satisfying the following relationships: $f_0 = 0.65$ GHz, $f_1 - f_0 = 0.112$ MHz, $f_2 - f_0 = 0.241$ MHz, $f_3 - f_0 = 2.671$ MHz, and for the phases measured by the phase measuring unit **120** set to: $\phi_0 = 66.3745$ deg, $\phi_1 = 339.2858$ deg, $\phi_2 = 348.2641$ deg, and $\phi_3 = 40.1806$ deg.

In this example, the maximal values for the additives M_0 , M_1 and M_2 , calculated by the processing system **13** by using the algorithms described above and the equations (4) or (5) have been obtained as: $M_{0max} = 30$, $M_{1max} = 35$, $M_{2max} = 685$. In turn, the number of the cycles N_0 of the first signal frequency component has been obtained as $N_0 = 1.0203 \times 10^4$. Accordingly, the calculated distance D between the transmitting unit **12** and the object **11** has been obtained as 158.18 km.

According to another aspect of the present technique, the processing system **13** is configured for determining location data of the object **11**. This location data, in general, may include various parameters associated with three location coordinates (spatial coordinates) $x(t)$, $y(t)$ and $z(t)$ of the object at time t and a system time T .

Referring to **Fig. 2**, a schematic block diagram of a positioning system **100** configured for determining location data of an object **11** is illustrated, according to an embodiment of the present invention. According to this embodiment, the positioning system **100** includes four transmitting units **12a-12d**. Each transmitting unit has a predetermined location characterized by a set of corresponding spatial location coordinates. In particular, the transmitting unit **12a** has coordinates (x_a, y_a, z_a) , the transmitting unit **12b** has coordinates (x_b, y_b, z_b) , the transmitting unit **12c** has coordinates (x_c, y_c, z_c) and the transmitting unit **12d** has coordinates (x_d, y_d, z_d) . It should be noted that clocks of the transmitting units **12a-12d** can be synchronized or unsynchronized with the clock of the receiver system **111**. When the clocks of transmitting units **12a-12d** are unsynchronized, each clock operates with its corresponding time t_a , t_b , t_c , and t_d , which is different from the time of the receiver system **111**.

The positioning system **100** also includes a receiver system **111** mounted on the object **11** having location coordinates $(x(t), y(t), z(t))$ at time t .

Each of the transmitting units **12a-12d** transmits a multi-frequency signal having a predetermined number L (at least two) of signal frequency components.

The receiver system **111** is configured to determine the phase data ϕ_i of each signal frequency component for each of the multi-frequency signals upon receiving the multi-frequency signals from all the transmitting units **12a-12d**.

The positioning system **100** also includes a processing system **13** configured to
 5 receive the phase data ϕ_i of each signal frequency component for each of the multi-frequency signals from the receiver system **111**, and to determine distances D_a , D_b , D_c and D_d from each transmitting unit **12a**, **12b**, **12c** and **12d** to the object **11**, correspondingly.

Once the distances D_a , D_b , D_c and D_d are determined, the processing system **13**
 10 can calculate the location data coordinates $(x(t), y(t), z(t))$ of the receiver **111** mounted on the object **11**, and when desired can also be synchronized by determining the system time T .

Accordingly, the processing system **13** can be configured for determining the system time T by solving the following system of equations:

15

$$c(T - \Delta t_a) = \sqrt{(x(t) - x_a)^2 + (y(t) - y_a)^2 + (z(t) - z_a)^2} \quad (7a)$$

$$c(T - \Delta t_b) = \sqrt{(x(t) - x_b)^2 + (y(t) - y_b)^2 + (z(t) - z_b)^2} \quad (7b)$$

$$c(T - \Delta t_c) = \sqrt{(x(t) - x_c)^2 + (y(t) - y_c)^2 + (z(t) - z_c)^2} \quad (7c)$$

$$c(T - \Delta t_d) = \sqrt{(x(t) - x_d)^2 + (y(t) - y_d)^2 + (z(t) - z_d)^2}, \quad (7d)$$

20

where $c(T - \Delta t_a)$, $c(T - \Delta t_b)$, $c(T - \Delta t_c)$ and $c(T - \Delta t_d)$ are the distances between the receiver system **111** mounted on the object **11** and the transmitting units **12a**, **12b**, **12c**, and **12d**, correspondingly.

It should be understood that the number of transmitting units can be selected in
 25 accordance with the number K of unknown location parameters of the system.

When desired, the processing system **13** is further configured for determining kinematic data indicative of velocity and acceleration of the object. The determining is based on the location data of the receiver **111** and the system time T . The kinematic data may, for example, be determined by taking time derivatives from the location data
 30 coordinates $(x(t), y(t), z(t))$ of the receiver **111** mounted on the object **11**.

In the cases where the system time T cannot be determined directly (e.g. clocks of the transmitters are not synchronized with the clock of the receiver system **111**), the

processing system **13** is configured for receiving the phase data ϕ_i of each signal frequency component for each of the multi-frequency signals from the receiver system **111** and determining kinematic data based on the phase data ϕ_i .

More specifically, the processing system **13** is configured for determining distances and kinematic data in accordance with phase difference of each signal frequency component for each of the multi-frequency signals. The phase difference is measured with a predetermined measurement rate T_s , thereby the distance D between each transmitting unit and the object and kinematic data can be determined at each time t .

It should be noted that when the system is not synchronized (i.e. clocks of the transmitters are not synchronized with the clock of the receiver system **111**), a pseudo-range is determined for each transmitting unit. Such a pseudo-range does not provide the accurate distance between the transmitting unit and the object, however, changes in location of the object (due to the object motion) can still be determined accurately. Upon determining the distance D for each time t , the kinematic data can be determined.

Referring to **Fig. 3**, a schematic block diagram of a positioning system **100** is illustrated, according to an embodiment of the present invention.

For example, as shown in **Fig. 3**, if the system time T is known, while three other location parameters, (such as location data coordinates $(x(t), y(t), z(t))$ of the receiver **111** mounted on the object **11**) are unknown, the positioning system **100** includes three transmitting units **12a**, **12b** and **12c**. Each transmitting unit has a certain location characterized by a set of corresponding spatial location coordinates. Specifically, the transmitting unit **12a** has coordinates (x_a, y_a, z_a) , the transmitting unit **12b** has coordinates (x_b, y_b, z_b) , and the transmitting unit **12c** has coordinates (x_c, y_c, z_c) .

Accordingly, the processing system **13** can be configured to determine these three location coordinates $x(t)$, $y(t)$ and $z(t)$ of the object by solving the system of the equations:

$$D_a = \sqrt{(x(t) - x_a)^2 + (y(t) - y_a)^2 + (z(t) - z_a)^2} \quad (8a)$$

$$D_b = \sqrt{(x(t) - x_b)^2 + (y(t) - y_b)^2 + (z(t) - z_b)^2} \quad (8b)$$

$$D_c = \sqrt{(x(t) - x_c)^2 + (y(t) - y_c)^2 + (z(t) - z_c)^2}, \quad (8c)$$

where D_a , D_b and D_c are the distances between the object **11** mounted on the receiver system **13** and the transmitting units **12a**, **12b** and **12c**, correspondingly, that can be obtained as described herein above.

In the case, when one of the location data coordinates ($x(t)$, $y(t)$, $z(t)$) is known,
5 for example a moving car or a ship, where the altitude $z(t)$ is known and does not change, only two of the transmitting units (for example, transmitting units **12a**, **12b**) are needed to determine the two remaining data coordinates ($x(t)$, $y(t)$).

Accordingly, the processing system **13** can be configured to determine these two location coordinates $x(t)$ and $y(t)$ of the object by solving the system of the equations:

10

$$D_a = \sqrt{(x(t) - x_a)^2 + (y_a)^2 + (z(t) - z_a)^2} \quad (8d)$$

$$D_b = \sqrt{(x(t) - x_b)^2 + (y_b)^2 + (z(t) - z_b)^2} \quad (8e).$$

As such, those skilled in the art to which the present invention pertains, can
15 appreciate that while the present invention has been described in terms of preferred embodiments, the concept upon which this disclosure is based may readily be utilized as a basis for the designing of other structures, systems and processes for carrying out the several purposes of the present invention.

Also, it is to be understood that the phraseology and terminology employed herein
20 are for the purpose of description and should not be regarded as limiting.

Finally, it should be noted that the word “comprising” as used throughout the appended claims is to be interpreted to mean “including but not limited to”.

It is important, therefore, that the scope of the invention is not construed as being limited by the illustrative embodiments set forth herein. Other variations are possible within
25 the scope of the present invention as defined in the appended claims. Other combinations and sub-combinations of features, functions, elements and/or properties may be claimed through amendment of the present claims or presentation of new claims in this or a related application. Such amended or new claims, whether they are directed to different combinations or directed to the same combinations, whether different, broader, narrower or
30 equal in scope to the original claims, are also regarded as included within the subject matter of the present description.

CLAIMS:

1. A positioning system (10) for determination of location data of an object (11) comprising:

at least one transmitting unit (12) configured to transmit a multi-frequency signal

5 comprising at least two different signal frequency components;

a receiver system (111) mounted on the object (11) and configured to receive the multi-frequency signals from said at least one transmitting unit (12), and to determine phases of each signal frequency component of the multi-frequency signal; and

a processing system (13) being in data communication with the receiver system
10 (111), and configured to receive the phases of each signal frequency component of the multi-frequency signal, and to determine a distance D between said at least one transmitting unit (12) and the object (11), and the location data of the object.

2. The system of claim 1, wherein the receiver (111) is configured for:

receiving the multi-frequency signals provided by said at least one transmitting unit (12)

15 analyzing the multi-frequency signals, wherein the multi-frequency signal includes a sum of a predetermined number L of signal frequency components f_i , where i is a number index of the signal frequency components, $i=1, 2, \dots, L$; wherein the signal frequency components f_i are mutually prime numbers; and

determining said number L of the signal frequency components f_i of each of said
20 multi-frequency signals.

3. The system of claim 2, wherein the distance D between said at least one transmitting unit (12) and the object (11) is determined by $D = c\Delta t$, where c is the light speed, and Δt is the time of propagation of the multi-frequency signals between said at least one transmitting unit (12) and the object (11), the time is determined from an equation:

25
$$\Delta t = \frac{\phi_i + 2\pi N_i}{2\pi f_i}$$

where ϕ_i is the phase of an i -th signal frequency component determined by the receiver (111), N_i is a number of wave cycles of an i -th signal frequency component spanned on the distance D , and where a number i of the signal frequency component f_i is selected from 0, 1, 2 and 3.

30 4. The system of claim 3, wherein a number of the signal frequency components f_i transmitted by said at least one transmitting unit (12) is four, f_0, f_1, f_2 , and f_3 , and wherein

the processing system (13) is configured for determining a number N_0 of cycles of the first signal frequency component f_0 by using any one of the following equations:

$$N_0 = -\frac{f_0\phi_1 - f_1\phi_0 + 2\pi M_0 f_0}{2\pi(f_0 - f_1)}$$

$$N_0 = -\frac{f_0\phi_2 - f_2\phi_0 + 2\pi M_1 f_0}{2\pi(f_0 - f_2)}$$

5 and

$$N_0 = -\frac{f_0\phi_3 - f_3\phi_0 + 2\pi M_2 f_0}{2\pi(f_0 - f_3)},$$

where M_0 , M_1 , and M_2 are additives to the number of cycles N_0 for the signal frequency components f_1 , f_2 , f_3 , correspondingly.

5. The system of claim 4, wherein M_0 and M_1 are determined by using the following
10 algorithm:

for each M_0 selected from 0 to $(M_{0\max}-1)$ and for each M_1 selected from 0 to $(M_{1\max}-1)$, the processing system (13) calculates integer numbers corresponding to M_0 and M_1 so as to satisfy an equation:

$$\frac{f_0\phi_1 - f_1\phi_0 + 2\pi M_0 f_0}{f_0 - f_1} = \frac{f_0\phi_2 - f_2\phi_0 + 2\pi M_1 f_0}{f_0 - f_2},$$

15 where $M_{0\max} = \text{round}[2\pi(f_1 - f_0)T_s]$ and where $M_{1\max} = [2\pi(f_2 - f_1)T_s]$ where T_s is the measurement rate.

6. The system of claim 4, wherein M_0 and M_1 are determined from an equation:

$$\Delta p_{\max} := \left| \text{floor} \left[\frac{f_0\phi_1 - f_1\phi_0 + 2\pi \cdot \text{mod}(\max, \text{Ma0}) \cdot f_0}{2\pi \cdot (f_0 - f_1)} \right] - \text{floor} \left[\frac{f_0\phi_2 - f_2\phi_0 + 2\pi \cdot \text{floor} \left(\frac{\max}{\text{Ma0}} \right) \cdot f_0}{2\pi \cdot (f_0 - f_2)} \right] \right|$$

by calculating integer numbers satisfying a condition $\Delta p_{\max}=0$ for each $\max$ selected from
20 0 to $(M_{0\max} \cdot M_{1\max}) - 1$, where $M_{0\max} = \text{round}[2\pi(f_1 - f_0)T_s]$ and where $M_{1\max} = \text{round}[2\pi(f_2 - f_1)T_s]$ where T_s is the measurement rate, and $\text{Ma0} = M_{0\max}$ or $M_{1\max}$.

7. The system of claim 4 or 5, wherein the processing system (13) is configured to calculate M_2 by solving an equation:

$$\frac{f_0\phi_1 - f_1\phi_0 + 2\pi M_0 f_0}{f_0 - f_1} = \frac{f_0\phi_3 - f_3\phi_0 + 2\pi M_2 f_0}{f_0 - f_3}.$$

25 8. The system of claim 3, wherein the processing system (13) is further configured to receive the phase data ϕ_i of each signal frequency component for each of the multi-frequency signals from the receiver system (111), and to determine kinematic data based

on the phase data ϕ , said kinematic data selected from velocity and acceleration of the object.

- 9.** The system of claim 1, wherein the system comprising three transmitting units (12a, 12b, 12c) having coordinates (x_a, y_a, z_a) , (x_b, y_b, z_b) and (x_c, y_c, z_c) , and the determination
5 of the location data includes calculating three location coordinates $x(t)$, $y(t)$ and $z(t)$ of the object at time t , correspondingly; and

wherein the processing system (13) is configured to determine the three location coordinates $x(t)$, $y(t)$ and $z(t)$ of the object (11) by using the following equations:

$$\begin{aligned} D_a &= \sqrt{(x(t) - x_a)^2 + (y(t) - y_a)^2 + (z(t) - z_a)^2} \\ D_b &= \sqrt{(x(t) - x_b)^2 + (y(t) - y_b)^2 + (z(t) - z_b)^2} \\ D_c &= \sqrt{(x(t) - x_c)^2 + (y(t) - y_c)^2 + (z(t) - z_c)^2}, \end{aligned}$$

where D_a , D_b and D_c are distances from said three transmitting units (12a, 12b, 12c) to the receiver system (111), correspondingly.

- 10.** The system of claim 1, wherein the processing system (13) comprising four
15 transmitting units (12a, 12b, 12c, 12d) having coordinates (x_a, y_a, z_a) , (x_b, y_b, z_b) , (x_c, y_c, z_c) and (x_d, y_d, z_d) , and wherein the processing system (13) is configured to determine the three location coordinates $x(t)$, $y(t)$ and $z(t)$ of the object (11) and for determining system time T by solving the following system of equations:

$$\begin{aligned} c(T - \Delta t_a) &= \sqrt{(x(t) - x_a)^2 + (y(t) - y_a)^2 + (z(t) - z_a)^2} \\ c(T - \Delta t_b) &= \sqrt{(x(t) - x_b)^2 + (y(t) - y_b)^2 + (z(t) - z_b)^2} \\ c(T - \Delta t_c) &= \sqrt{(x(t) - x_c)^2 + (y(t) - y_c)^2 + (z(t) - z_c)^2} \\ c(T - \Delta t_d) &= \sqrt{(x(t) - x_d)^2 + (y(t) - y_d)^2 + (z(t) - z_d)^2}, \end{aligned}$$

where T is a system time which is common to said four transmitting units (12a, 12b, 12c, 12d) and where $c(T - \Delta t_a)$, $c(T - \Delta t_b)$, $c(T - \Delta t_c)$ and $c(T - \Delta t_d)$ are the distances
25 between said transmitting units (12a, 12b, 12c, 12d) and said receiver system (111) mounted on the object (11), correspondingly.

- 11.** A positioning method for determining location data of an object, comprising:
providing the system (1) of claim 1;
transmitting a multi-frequency signal comprising at least two different
30 frequencies; and

measuring the phases of each signal frequency component of the multi-frequency signal;

determining a distance D between said at least one transmitting unit (12) and the object, and the location data of the object.

- 5 **12.** The method of claim 11, wherein the receiver (111) is configured for:
receiving the multi-frequency signals provided said at least one transmitting unit (12),
analyzing the multi-frequency signals, wherein the multi-frequency signal includes a sum of
a predetermined number L of signal frequency components f_i , where i is a number index of
the signal frequency components, $i = 1, 2, \dots, L$; wherein the signal frequency components f_i
10 are mutually prime numbers; and

determining said number L of the signal frequency components f_i of each of said multi-frequency signals.

- 13.** The method of claim 12, wherein the distance D between said at least one transmitting unit (12) and the object (11) is determined by $D = c \Delta t$, where c is the light
15 speed, and Δt is the time of propagation of the multi-frequency signals between said at least one transmitting unit and the object (11), the time is determined from an equation:

$$\Delta t = \frac{\phi_i + 2\pi N_i}{2\pi f_i}$$

- where ϕ_i is the phase of an i -th signal frequency component determined by the receiver (111), and N_i is a number of wave cycles of an i -th signal frequency component spanned
20 on the distance D , and where a number i of the signal frequency component f_i is selected from 0, 1, 2 and 3.

- 14.** The method of claim 13, wherein a number of the signal frequency components f_i transmitted by said at least one transmitting unit is four, f_0, f_1, f_2 , and f_3 , and wherein the method includes determining a number N_0 of cycles of the first signal frequency component
25 f_0 by using any one of the equations:

$$N_0 = -\frac{f_0\phi_1 - f_1\phi_0 + 2\pi M_0 f_0}{2\pi(f_0 - f_1)}$$

$$N_0 = -\frac{f_0\phi_2 - f_2\phi_0 + 2\pi M_1 f_0}{2\pi(f_0 - f_2)}$$

and

$$N_0 = -\frac{f_0\phi_3 - f_3\phi_0 + 2\pi M_2 f_0}{2\pi(f_0 - f_3)}$$

where M_0, M_1 , and M_2 are additives to the number of cycles N_0 for the signal frequency components f_1, f_2, f_3 , correspondingly.

15. The method of claim 14, comprising determining M_0 and M_1 by using the following algorithm:

- 5 for each M_0 selected from 0 to $(M_{0\max}-1)$ and for each M_1 selected from 0 to $(M_{1\max}-1)$, calculating, by the processing system (13), integer numbers corresponding to M_0 and M_1 , which satisfy an equation:

$$\frac{f_0\phi_1 - f_1\phi_0 + 2\pi M_0 f_0}{f_0 - f_1} = \frac{f_0\phi_2 - f_2\phi_0 + 2\pi M_1 f_0}{f_0 - f_2}$$

- 10 where $M_{0\max} = \text{round}[2\pi(f_1 - f_0)T_s]$ and where $M_{1\max} = \text{round}[2\pi(f_2 - f_1)T_s]$ where T_s is the measurement rate.

16. The method of claim 14, comprising determining M_0 and M_1 from an equation:

$$\Delta p_{\text{mx}} := \left\lfloor \frac{f_0\phi_1 - f_1\phi_0 + 2\pi \cdot \text{mod}(mx, Ma0) \cdot f_0}{2\pi \cdot (f_0 - f_1)} \right\rfloor - \left\lfloor \frac{f_0\phi_2 - f_2\phi_0 + 2\pi \cdot \text{floor}\left(\frac{mx}{Ma0}\right) \cdot f_0}{2\pi \cdot (f_0 - f_2)} \right\rfloor$$

- by calculating integer numbers satisfying a condition $\Delta p_{\text{mx}}=0$ for each mx selected from 0 to $(M_{0\max} \cdot M_{1\max}) - 1$, where $M_{0\max} = \text{round}[2\pi(f_1 - f_0)T_s]$ and where $M_{1\max} = \text{round}[2\pi(f_2 - f_1)T_s]$ where T_s is the measurement rate, and $Ma0 = M_{0\max}$ or $M_{1\max}$.

17. The method of claim 14 or 15, comprising calculating M_2 by solving an equation:

$$\frac{f_0\phi_1 - f_1\phi_0 + 2\pi M_0 f_0}{f_0 - f_1} = \frac{f_0\phi_3 - f_3\phi_0 + 2\pi M_2 f_0}{f_0 - f_3}$$

- 18.** The method of claim 12, wherein determining of kinematic data includes receiving the phase data ϕ_i of each signal frequency component for each of the multi-frequency signals from the receiver system (111) and to determining the kinematic data based on the phase data ϕ_i , said kinematic data selected from velocity and acceleration of the object (11).

- 19.** The method of claim 11, wherein the system comprises three transmitting units (12a, 12b, 12c) having coordinates (x_a, y_a, z_a) , (x_b, y_b, z_b) and (x_c, y_c, z_c) , the method includes determining location data, and includes calculating three location coordinates $x(t)$, $y(t)$ and $z(t)$ of the object (11) at time t , correspondingly; and wherein the processing system (13) is configured to determine the three location coordinates $x(t)$, $y(t)$ and $z(t)$ of the object (11) by using equations: