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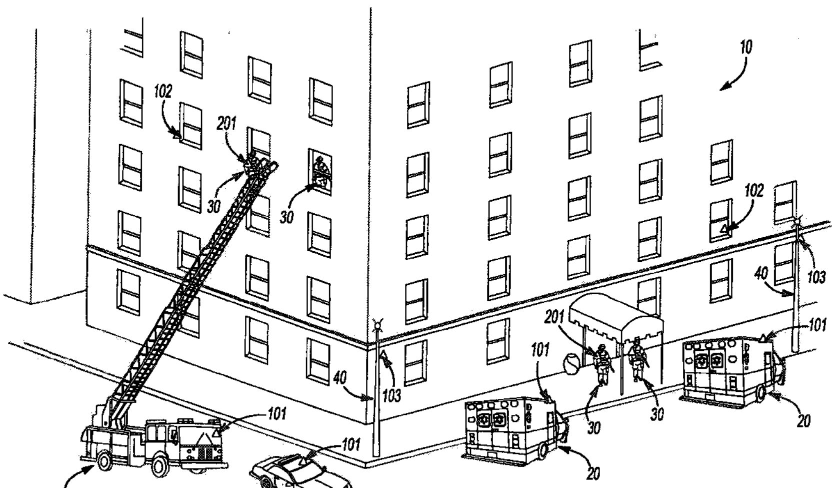

Fig. - 1

(57) Abstract: Methodologies are disclosed for determining the height of a target [201] and its horizontal location in three dimensional space using a network of base stations [101,102,103]. In one embodiment recursive two dimensional trilateration is used to determine the height, in another embodiment height is provided externally and used to correct the ranges used in two dimensional trilateration.

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MULTI-LEVEL TRACKING

[0001] The present application claims the benefit of the filing date of United States Provisional application Serial No. 61/105,767 filed October 15, 2008, which is herein incorporated by reference in its entirety for all purposes.

FIELD OF THE INVENTION

[0002] The field of the present invention is directed generally to the use of an ad hoc network for tracking and more particularly to the use of an ad hoc network having base stations placed within or around a multi-story building for tracking a target to determine the location, including elevation or floor location, of the target.

BACKGROUND OF THE INVENTION

[0003] Commonly owned U.S. Patent No. 7,403,783, the contents of which are hereby expressly entirely incorporated by reference for all purposes, discusses initializing a network of at least three base stations to determine their relative locations to each other in a two-dimensional coordinate system. The range to a target can be measured by the time of arrival (TOA) or time of difference arrival (TDOA) of at least one signal from three or more of the base stations. Provided these ranges, the location or position of the target on the two-dimensional coordinate system can be calculated directly.

[0004] For example, the technology discussed in U.S. Patent No. 7,403,783 which is in at least part, if not in whole applicable in the present invention discusses an ad hoc network using a wireless radio network for determining a target location with high positioning accuracy and fast update rate. Such a network includes multiple base stations and at least one target unit, linked and in communication together via signal communication, such as radio frequency communication, or more particularly with via high frequency ultra-wide bandwidth (UWB) wireless ranging and communication (RAC) transceivers and location schemes. Due to the UWB frequency spectrum and thus its high penetration, placement of the base stations may not be critical. The UWB RAC scheme ensures the desired accuracy in distance measurements and station identification. The location schemes employ fast direct closed-form solutions for self-organizing local and global geographic (e.g. GPS) coordinate systems, and determining position of base stations and targets within the desired coordinate system. U.S. Patent No.

7,403,783 further discusses initializing a network of at least three base stations to determine their relative location to each other in a coordinate system; measuring, at the target, the time of arrival of at least one signal from each of three base stations, and then calculating the location of the target on the coordinate system. The initializing step in U.S. Patent No. 7,403,783 utilizes at least three base stations and preferably at least four base stations. The base stations are transceivers that are capable of both receiving and transmitting signals. The target and/or multiple targets may also function as base stations. The base stations may also be mobile and provide ranges while in motion.

[0005] It would prove beneficial to be able to determine the location of a target in a three-dimensional environment, such as a target located in a multi-level structure. For example, in an emergency scenario, where a fire has erupted in the interior of a multi-story building, it would be advantageous to be able to track the location and movement of targets, such as emergency first responders, within the building.

[0006] Determining the location of a target in multi-level structures is often cumbersome, expensive, and inaccurate. Some proposed solutions separate floor or altitude determination from the more general tracking problem.

[0007] For example, altimeters / barometers (see U.S. Patent No. 7,162,368, the contents of which are hereby expressly entirely incorporated by reference for all purposes) can be used to detect changes in air pressure resulting from changes in altitude or evaluation. However, altimeters and/or barometers are often inaccurate and can vary in readings based upon weather fluctuations, and therefore may not provide an accurate and reliable source of elevation information. Furthermore, reliance on altimeters to determine floor level requires the user to supply a nominal floor height which may incorrectly assume equal floor spacing. Altimeters do not provide positioning information other than altitude. Additional hardware is required to determine the absolute position of a target.

[0008] Direct radio frequency (RF) transmission of floor level may also be used to determine floor location. U.S. Patent Application Publication Serial No. 2003/0104818, the contents of which are hereby expressly entirely incorporated by reference for all purposes, describes a method of floor level determination wherein transmitters are placed throughout a multi-story structure at critical points (near stairwells, elevators, exits) which explicitly broadcast floor location to a wireless device. This method does not provide positioning information of the target being tracked other than its floor location. Additional hardware is required to determine the absolute position of a target.

[0009] A number of solutions have been proposed to provide three-dimensional tracking within a multi-story structure. U.S. Patent Application Publication Serial No. 2009/0085741, the contents of which are hereby expressly entirely incorporated by reference for all purposes, discloses a method employing mobile radio-frequency identification (RFID) readers and fixed location RFID tags positioned throughout a structure. The readers are able to extract location information from the tags when they are in the vicinity of the tags. This method provides positional accuracy limited to the range to the tag being read. A drawback to this approach is the inverse relationship between positional accuracy and the number of deployed tags.

[0010] Three-dimensional positioning may also be performed using received signal strength identification (RSSI) techniques (see U.S. Patent Nos. 6,442,507, 6,839,560, 7,020,475, and U.S. Patent Application Publication Serial Nos. 2008/0055158, 2009/0033499, 2009/0033500 and 2009/0067392, the contents of which are hereby expressly entirely incorporated by reference for all purposes) wherein a target seeking to determine its location within a building detects, using a mobile device, the signal strength of one or more wireless base stations placed at known locations throughout the building. The measured signal strength may then be used to determine location via a signal-strength to location look-up table. The table may be derived empirically by recording the signal strength of the wireless base stations at known locations prior to tracking. The table may also be derived mathematically be taking into account a reference signal strength, the distance between the reference point and a known location, and the number of walls or other obstructions between the reference point and the known location. One drawback to this approach is inherent with RSSI itself, as signal strength may change rapidly due to changes in the layout of the building (obstruction by furniture, plants, people, etc.) as well as antenna orientation of the mobile device.

[0011] Similar to the RSSI methods described above, a distributed antenna system (see U.S. Patent No. 7,336,961 and U.S. Patent Application Publication Serial No. 2005/0143091, the contents of which are hereby expressly entirely incorporated by reference for all purposes) may be used for three-dimensional positioning. This method employs a plurality of antennas located within a multi-floor building, each antenna radiating to define a respective coverage area in which a mobile device can communicate. In operation, the system may determine that one of the antennas has received a strongest signal from the mobile device, indicating that the mobile device is within the geographic coverage area of the antenna. This approach has a number of shortcomings, including the inverse relationship between positional accuracy and the number of installed antennas as well as RSSI's dependence on physical layout stability.

[0012] Accordingly, it would prove beneficial to be able to determine the location of a target in a three-dimensional environment, such as a target located in a multi-level structure quickly, efficiently and accurately. For example, in an emergency scenario, where a fire has erupted in the interior of a multi-story building, it would be advantageous to be able to track the location and movement of targets, such as emergency first responders, within the building. Also advantageous, it would prove to be beneficial to track targets in scenario were no prior existing infrastructure has been implemented in an existing structure. The present invention seeks to at least accomplish at least some, if not all, or even more of these goals.

SUMMARY OF INVENTION

[0013] The present invention meets some or all of the above-mentioned needs by providing a method of determining position of a target in a three dimensional space. The invention may provide a method of determining the location of an individual who is carrying a target in a building, particular a building with multiple floors. In instances where there is an emergency in a building such as fire, first responders may be deployed into the building while having there position in the building monitors using the methods described herein. In situations where a first responder is injured or harmed, the first responder's location will be known so that appropriate assistance may be sent to his particular location in the building.

[0014] One aspect of the invention is directed towards a method of determining position of a target in a three dimensional space comprising providing a plurality of base stations, determining location of each of the plurality of base stations, determining ranges from the target to the plurality of base stations, determining height of the target, selecting ranges from a subset of base stations of the plurality of base stations, wherein the subset of base stations are at a same floor as the target, and calculating the position of the target using two dimensional trilateration using the ranges from a subset of base stations and the height of the target.

[0015] This aspect of the invention may be further characterized by one or any combination of the following: the method of determining position of a target in a three dimensional space wherein the determining the location of at least a portion of the plurality of base stations comprises initializing the plurality of base stations, wherein, during initializing, a first base station of the plurality of base stations sends a signal to a second base station and a third base station of the plurality of base stations to determine a distance between the first base station and the second base station and a distance between the first base station and the third base station and wherein the second base station sends a signal to the third base station to determine a distance between the second base station and the third base station, wherein the determining the location of each of the plurality of base stations comprises surveying the plurality of base stations at their locations, wherein the determining the range from the target to the plurality of base stations comprises measuring time of arrival of an at least one signal communicated between the target and the plurality of base stations, wherein the determining the range from the target to the plurality of base stations comprises measuring the time difference of arrival of an at least one signal communicated between the target and the plurality of base stations, wherein the determining the range from the target to the plurality of base stations comprises measuring the received signal strength of at least one signal communicated between the target and the plurality of base stations, associating a floor level with a base station of the plurality of base stations, wherein the determining the height of the target comprises measuring the received signal strength of at least one signal communicated between the target and the plurality of base stations, wherein the determining the height of the target comprises determining the floor level with the most base stations capable of ranging with the target.

[0016] Another aspect of the invention is directed towards a method of determining position of a target in a three dimensional space comprising providing a plurality of base stations, determining location of each of the plurality of base stations, determining ranges from the target to the plurality of base stations, determining height of the target relative to each of the plurality of base stations, determining projected ranges using the height of the target and the ranges from the target to the plurality of base stations, and calculating the position of the target using two dimensional trilateration using the projected ranges and the height of the target.

[0017] This aspect of the invention may be further characterized by one or any combination of the following: the method of determining position of a target in a three dimensional space wherein the determining the location of at least a portion of the plurality of base stations comprises initializing the plurality of base stations, wherein, during initializing, a first base station of the plurality of base stations sends a signal to a second base station and a third base station of the plurality of base stations to determine a distance between the first base station and the second base station and a distance between the first base station and the third base station and wherein the second base station sends a signal to the third base station to determine a distance between the second base station and the third base station, wherein the determining the location of each of the plurality of base stations comprises surveying the plurality of base stations at their locations, wherein the determining the range from the target to the plurality of base stations comprises measuring time of arrival of an at least one signal communicated between the target and the plurality of base stations, wherein the determining the range from the target to the plurality of base stations comprises measuring the time difference of arrival of an at least one signal communicated between the target and the plurality of base stations, wherein the determining the range from the target to the plurality of base stations comprises measuring the received signal strength of at least one signal communicated between the target and the plurality of base stations, associating a floor level with a base station of the plurality of base stations, wherein the determining the height of the target comprises determining the floor level with the most base stations capable of ranging with the target, wherein the determining the height of the target comprises minimizing the Euclidian norm error of the norm of the grouping of the positions returned from two dimensional trilateration, wherein the determining the height of the target comprises minimizing the averaged square error between the two-dimensional calculated and projected ranges resulting from two-dimensional trilateration between the target and base stations, wherein the determining the height of the target comprises minimizing the averaged square error between the three-dimensional calculated and measured ranges resulting from two-dimensional trilateration between the target and base stations.

[0018] Another aspect of the invention is directed towards a method of determining position of a target in a three dimensional space comprising providing a plurality of base stations, determining location of each of the plurality of base stations, determining height of the target, determining ranges to a subset of base stations from the plurality of base stations that are at the same floor as the target, and calculating the position of the target using two dimensional trilateration using the ranges to the subset of base stations and the height of the target.

[0019] This aspect of the invention may be further characterized by one or any combination of the following: the method of determining position of a target in a three dimensional space, wherein the determining the location of at least a portion of the plurality of base stations comprises initializing the plurality of base stations, wherein, during initializing, a first base station of the plurality of base stations sends a signal to a second base station and a third base station of the plurality of base stations to determine a distance between the first base station and the second base station and a distance between the first base station and the third base station and wherein the second base station sends a signal to the third base station to determine a distance between the second base station and the third base station, wherein the determining the location of each of the plurality of base stations comprises surveying the plurality of base stations at their locations, wherein the determining ranges to a subset of base stations from the plurality of base stations that are at the same floor as the target comprises measuring time of arrival of an at least one signal communicated between the target and the plurality of base stations, wherein the determining ranges to a subset of base stations from the plurality of base stations that are at the same floor as the target comprises measuring the time difference of arrival of an at least one signal communicated between the target and the plurality of base stations, wherein determining ranges to a subset of base stations from the plurality of base stations that are at the same floor as the target comprises measuring the received signal strength of at least one signal communicated between the target and the plurality of base stations, associating a floor level with a base station of the plurality of base stations, wherein the determining the height of the target combination thereof.

BRIEF DESCRIPTION OF THE DRAWINGS

[0020] Fig. 1 illustrates an embodiment of the invention used by fire fighters arriving at the scene of a building fire.

[0021] Fig. 2 is a diagram of an example of two-dimensional trilateration between a target and pairs of base stations from a set of three base stations when the target and base stations are coplanar.

[0022] Fig. 3 illustrates Pythagorean's Theorem as applied to a target ranging to a non-planar base station.

[0023] Fig. 4 exemplifies how error is introduced in determining the position of a target using two-dimensional trilateration in the event that the target and base stations are non-planar.

[0024] Fig. 5 is a flowchart of a method to determine target floor level by minimizing the Euclidean norm of the primary grouping of positions returned from two-dimensional trilateration to non-planar base stations.

[0025] Fig. 6 is a flowchart of a method to determine target floor level by minimizing the two-dimensional Euclidean norm of the calculated and projected ranges to non-planar base stations resulting from two-dimensional trilateration to the base stations.

[0026] Fig. 7 is a flowchart of a method to determine target floor level by minimizing the three-dimensional Euclidean norm of the calculated and measured ranges to non-planar base stations resulting from two-dimensional trilateration to the base stations.

[0027] Fig. 8 is a diagram of a recursive method to determine target height by minimizing the Euclidean norm of the primary grouping of positions returned from two-dimensional trilateration to non-planar base stations.

[0028] Fig. 9 is a diagram of a recursive method to determine target height by minimizing the averaged square error between the two-dimensional calculated and projected ranges resulting from two-dimensional trilateration between a target and non-planar base stations.

[0029] Fig. 10 is a diagram of a recursive method to determine target height by minimizing the averaged square error between the three-dimensional calculated and measured ranges resulting from two-dimensional trilateration between a target and non-planar base stations.

DETAILED DESCRIPTION

[0030] The present invention seeks to improve on the teachings of commonly owned U.S. Patent No. 7,403,783, the contents of which are hereby expressly entirely incorporated by reference for all purposes. Through the improvements, as described herein, the present invention provides a system for locating and tracking a target in a multi-story structure.

[0031] The tracking system for multi-level structures can use radio frequency (RF) ranging transceivers to track positions of moving targets. The system can utilize a solution to track a target in a horizontal two-dimensional scenario as disclosed in U.S. Patent No. 7,403,783, the contents of which are hereby expressly entirely incorporated by reference for all purposes, along with a correction operation for height differences between the target and base stations to determine target floor level location. The floor level of a target can be determined by the height of the target.

[0032] Figure 1 depicts an embodiment of the present multi-level tracking invention in use in a situation where a fire has erupted in a building 10. Emergency vehicles 20 have responded to the fire and have just arrived at the scene. Firefighters 30 are entering the building 10 and are carrying targets 201. Emergency vehicle base stations 101 are installed on the emergency vehicles 20 and building base stations 102 as well as external base stations 103 are installed within or in proximity to the building 10. In the emergency scenario depicted in Figure 1, where a fire has erupted in the interior of a multi-story building, it is possible using the methods disclosed herein to be able to track the location and movement of targets and/or the firefighters 30.

[0033] In one embodiment, the tracking system can operate by setting up an ad hoc system of a set of reference base stations, similar to the system disclosed in U.S. Patent No. 7,403,783, on each floor of a building. In another embodiment, the reference base stations may be previously installed at known locations on each floor of a building. The base stations compromise transceivers which are configured with a group identification number (group ID) and a unit identification number (unit ID). The transceivers of the base stations are assumed to be configured with a different group ID on each floor. When setting up an ad-hoc coordinate system, base stations may range to other base stations only if they share the same group ID. The unit ID's need not be unique, however no two transceivers with the same group ID may posses the same unit ID. It is assumed that targets possess group ID's distinct from those of the base stations. As is the case for base stations, it is assumed that no two targets have the same group and unit ID. While base stations need not be stationary, it is assumed that the height or floor level of each base station is known and available for use in trilateration. This information may be stored in the base station itself, or may be stored off-board. Likewise, it is also assumed that the height or floor level of targets used to calculate the position of another target is also available. In one embodiment, the tracking system determines the position, including floor level, of a target using ranges to base stations on the same floor. In another embodiment, the base stations may be set up anywhere within or outside of the building. It is contemplated that the targets can function as base stations. Therefore, targets can also function as base stations.

[0034] Two-dimensional tracking has several advantages over three-dimensional tracking. Two-dimensional tracking permits the use of double dipole antennas which increase range in the horizontal plane at the cost of less spread in the vertical angle. Two-dimensional tracking does not require a sufficient vertical spread of base stations as is required for traditional three-dimensional trilateration techniques. Furthermore, two-dimensional tracking also requires fewer base stations than those needed for three-dimensional tracking.

[0035] In one embodiment of the invention, target height may be determined by scanning through, or using the ranges to, the base stations as a function of group ID or floor level. If antenna orientation or signal strength of the transceivers is such that ranging may only occur between a target and base stations on the same floor, then it may be determined that the height of the target is the same as that of the base stations. In another embodiment of the invention, signal strength may be used to associate the target with base stations on the same floor. In another embodiment of the invention, the target height may be determined by associating it with the height of base stations, located on a common floor, which are able to range with the target in greatest number. It is envisioned that it may be beneficial to provide or update a list of base stations and targets in operation upon the initialization of a base station or target, or perhaps when a target enters a building. Furthermore, the list may correlate base stations and other targets with floor levels or heights. If available, information may be provided by GPS identify the list to be used from a larger database.

[0036] The height or floor level of a base station or a target can also be determined by using a barometer whose altitude reading can be correlated with the elevation of the floor height to determine the floor the base station or target are located at.

[0037] The height or floor level of a base station or a target can also be determined by manual entry of the floor number where an individual with knowledge of the floor level location of the base station or target manually enters or communicates the floor level where the base station or target are located at.

[0038] The height or floor level of a base station or target can also be determined by using an RFID device. A RFID tag or reader can be situated in proximity to the entrance to a floor level, where an object or target that enters the particular floor level would communicate with an RFID device to determine floor level or height to the object or target where the object or target is now located at.

[0039] The height or floor level of a base station or target can also be determined by using a barcode reader. A barcode can be placed in proximity to the entrance of a floor level, where an object or target that enters the particular floor level would scan the barcode to determine floor level or height to the object or target where the object or target is now located at.

[0040] The height or floor level of a base station or target can also be determined by using a magnetic device. A magnetic strip can be situated in proximity to the entrance to a floor level, where an object or target that enters the particular floor level would swipe a magnetic strip to determine floor level or height to the object or target where the object or target is now located at.

[0041] The height or floor level of a base station or target can also be determined by using a communication interface. A contact based communication device (like an iButton by Maxim) can be situated in proximity to the entrance to a floor level, where an object or target that enters the particular floor level would touch the device and exchange communication with the device through the contact area to determine floor level or height to the object or target where the object or target is now located at.

[0042] Two-Dimensional Trilateration: Target and base stations in same plane

[0043] Provided accurate range measurements, two-dimensional trilateration between a target and pairs of base stations from a set of n base stations will result in a set S consisting of $\frac{n!}{2(n-2)!}$ pairs of points, $\left\{\left(x_{i,j},y_{i,j}\right)_1,\left(x_{i,j},y_{i,j}\right)_2\right\}$, coincident with the intersection of the circles centered at base stations i and j with radii r_i and r_j corresponding to the ranges between the target and base stations i and j, respectively. Formally, let $\sum_{i=1}^{n-1}\sum_{j=i+1}^{n}\left\{\left(x_{i,j},y_{i,j}\right)_1,\left(x_{i,j},y_{i,j}\right)_2\right\}$ denote the totality of the point pairs contained in S.

[0044] Provided accurate range measurements, two-dimensional trilateration between a target (*201*) and pairs of base stations from a set of three base stations (*1*, *2*, *3*) will return results similar to that shown in Figure 2, where r_i denotes the range from base station i to the target. The Euclidean norm $\left\|(x_1,y_1),(x_2,y_2)\right\|=\sqrt{(x_1-x_2)^2+(y_1-y_2)^2}$ may be used to group the six intersection points into four sets as a function of the relative distances between them: $\{(x_{1,2},y_{1,2})_1$, $(x_{1,3},y_{1,3})_1$, $(x_{2,3},y_{2,3})_1\}$, $\{(x_{1,2},y_{1,2})_2\}$, $\{(x_{1,3},y_{1,3})_2\}$ and $\{(x_{2,3},y_{2,3})_2\}$. The coincident points $(x_{1,2},y_{1,2})_1$, $(x_{1,3},y_{1,3})_1$ and $(x_{2,3},y_{2,3})_1$ correspond to the location of the target. In this example, the primary grouping $\{(x_{1,2},y_{1,2})_1$, $(x_{1,3},y_{1,3})_1$, $(x_{2,3},y_{2,3})_1\}$, $\{(x_{1,2},y_{1,2})_2\}$, $\{(x_{1,3},y_{1,3})_2\}$ has a Euclidean norm of zero.

[0045] Two-Dimensional Trilateration: Target and base stations in different planes

[0046] Consider now a three-dimensional case in which ranging occurs between a target and coplanar base stations which are non-coplanar with the target. Error is introduced in determining the position of a target using two-dimensional trilateration in the event that the target and base stations are non-planar. The basis for this error is illustrated in Figure 3 where a range of $r=\sqrt{d^2+h^2}$ is measured between a target (*201*) located at $(0,0,h)$ in the plane *z* = *h* and a base station (*101*) located at $(d,0,0)$ in the *x-y* plane. Results from two-dimensional trilateration will be in error since the target is assumed to lie in the *x-y* plane with the base stations. Correct results in the *x-y* plane will only be returned in the event that *d*, rather than *r*, is used for trilateration. The length *d* corresponds to the measured range *r* projected onto the same *z*-plane as the base station, and is thus referred to as the projected range. Provided accurate range measurements, the use of the measured range *r* rather than the projected range *d* will always result in error since $r>d$ for all non-zero *h*. It is understand that the projected range equals the measured range in the event that the height difference between the target and base station is zero.

[0047] If the measured ranges between the target and base stations are larger than the actual ranges, then the three circles used for trilateration will no longer intersect at a single point, as shown in Figure 4. In this case, the Euclidean norm of the grouping $\{(x_{1,2},y_{1,2})_1$, $(x_{1,3},y_{1,3})_1$, $(x_{2,3},y_{2,3})_1\}$ is non-zero and is an indication of a height mismatch between the target (*201*) and the base stations (*1, 2, 3*).

[0048] As a specific example, consider the case where a target is located at (x,y,z) = $(220,20,20)$ and base stations 1, 2, 3 and 4 are located at $(0,0,0)$, $(250,0,0)$, $(0,250,0)$ and $(250,250,0)$, respectively. The ranges between the target and base stations 1, 2, 3 and 4 are 221.8107, 41.2311, 318.9044 and 232.8089, respectively. The results of two-dimensional trilateration of the target and base station pairs are listed in Table 1. A grouping of all elements in the set $\{(x_{i,j},y_{i,j})_1\}$ results in a Euclidean norm of 17.57. A Euclidean norm of 8.49 results if $(x_{2,3},y_{2,3})_1$ and $(x_{2,4},y_{2,4})_1$ are excluded from the grouping.

Base Stations used to trilaterate	$(x_{i,j},y_{i,j})_1$	$(x_{i,j},y_{i,j})_2$

1 : 2	(220.00, 28.28)	(220.00, -28.28)
1 : 3	(220.91, 20.00)	(-220.91, 20.00)
1 : 4	(221.00, 19.01)	(19.01, 221.00)
2 : 3	(210.00, 10.00)	(240.00, 40.00)
2 : 4	(213.94, 20.00)	(286.06, 20.00)
3 : 4	(220.00, 19.13)	(220.00, 480.87)

Table 1: Trilateration performed with measured ranges

[0049] The *x-y* plane projected ranges, *d*, may be calculated using the equation $d=\sqrt{r^2-h^2}$. In the absence of ranging errors, when the correct height, *h*, of the target relative to the base stations is used in this equation, the Euclidean norm of the prime grouping becomes zero when *d* rather than *r* is used during trilateration. From the previous example, the projected ranges between the target and base stations 1, 2, 3 and 4 are 220.9072, 36.0555, 318.2766 and 231.9483, respectively. The results of two-dimensional trilateration performed with the projected ranges are listed in Table 2. Note that the correct (*x*,*y*) coordinates of (220.0, 20.0) are returned.

Base Stations used to trilaterate	$(x_{i,j}, y_{i,j})_1$	$(x_{i,j}, y_{i,j})_2$
1 : 2	(220.00, 20.00)	(220.00, -20.00)
1 : 3	(220.00, 20.00)	(-220.00, 20.00)
1 : 4	(220.00, 20.00)	(20.00, 220.00)
2 : 3	(220.00, 20.00)	(230.00, 30.00)
2 : 4	(220.00, 20.00)	(280.00, 20.00)
3 : 4	(220.00, 20.00)	(220.00, 480.00)

Table 2: Trilateration performed with projected ranges

[0050] The base stations need not be coplanar as assumed in the previous example. When base stations are placed at differing heights, the equation $d_i=\sqrt{r_i^2-h_i^2}$ may be used, where r_i is the range between a target located at (x, y, z) and a base station located at (x_i, y_i, z_i),

$h_i = |z - z_i|$ is the difference in height between the target and base station, and d_i is the projection of the range onto the z_i plane. In practice, the height of the target relative to the base stations is not known but may be solved for in an iterative process involving the projected ranges of the target to the base stations.

[0051] In one embodiment of the invention, target height may be determined using ranges between the target and base stations on a floor by floor basis as outlined in Figure 5. Here it is assumed that ranging can occur between the target and base stations located on several floors. In this embodiment, target height is determined by minimizing the Euclidean norm of the primary grouping resulting from two-dimensional trilateration.

[0052] In another embodiment, target height may be determined using ranges between the target and base stations on a floor by floor basis as outlined in Figure 6. In this embodiment, target height is determined by minimizing the two-dimensional Euclidean norm of the calculated and projected ranges to non-planar base stations resulting from two-dimensional trilateration to the base stations.

[0053] In another embodiment, target height may be determined using ranges between the target and base stations on a floor by floor basis as outlined in Figure 7. In this embodiment, target height is determined by minimizing the three-dimensional Euclidean norm of the calculated and measured ranges to non-planar base stations resulting from two-dimensional trilateration to the base stations.

[0054] In another embodiment, depicted in Fig. 8, the assumed height, *h*, of a target may be recursively adjusted to minimize the Euclidean norm of the primary grouping resulting from trilateration using the projected ranges d_i to *n* base stations, each of which are at possibly distinct heights. Assuming accurate range measurements, the target's true height will correspond to the assumed height resulting in the smallest norm.

[0055] In another embodiment, shown in Fig. 9, the assumed height, *h*, of a target may be recursively adjusted to minimize the two-dimensional squared error between the calculated ranges, $\hat{d}_i$, between a target located at (x, y, h) with an assumed height *h* and a base station located at (x_i, y_i, z_i), and the projected ranges d_i between the base station and the targets trilaterated position where two-dimensional trilateration occurs using d_i. Assuming accurate range measurements, the target's true height will correspond to the assumed height resulting in the smallest squared error.

[0056] In another embodiment, shown in Fig. 10, the assumed height, h, of a target may be recursively adjusted to minimize the three-dimensional squared error between the calculated ranges, $\hat{r}_i$, between a target located at (x, y, h) with an assumed height h and a base station located at (x_i, y_i, z_i), and the measured ranges r_i between the base station and the targets trilaterated position where two-dimensional trilateration occurs using d_i. Assuming accurate range measurements, the target's true height will correspond to the assumed height resulting in the smallest squared error.

[0057] It is understood that there are many other ways in which to compute or minimize the error and norms in the above examples other than those shown. In addition, it is understood that the methods previously described may benefit from filtering, hysteresis and other forms of logic when determining the height of a target. Although examples have been given showing trilateration between a target and two other base stations or target, it is understood that the examples apply to instances more than three entities trilaterate at once.

[0058] It is understood that the above methods may be employed when ranging occurs between a target and other targets as well as base stations. It is assumed in such instances that the targets whose position is not being calculated have a previously computed position that may be provided when calculating the other target's position. It is understood that different weighting may be applied to results utilizing ranges between targets and other targets in the event that the position of the targets is deemed to be less reliable than those of the base stations used for trilateration.

[0059] Although the above examples assume that perfect range measurements are available, it is understood that this is likely not the case in all circumstances. In the event that range measurements become distorted as a function of distance or object (floor, etc.) penetration, it is understood that this may be accounted for to some degree by taking into account the distance and obstacles between two ranging devices.

[0060] It is understood that the trilateration techniques described herein are applicable to ranges determined using both TDOA and TOA techniques.

[0061] Unless stated otherwise, dimensions and geometries of the various structures depicted herein are not intended to be restrictive of the invention, and other dimensions or geometries are possible. Plural structural components can be provided by a single integrated structure. Alternatively, a single integrated structure might be divided into separate plural components. Similarly, specific features or components described in the different embodiments of the blocks may be used with other embodiments or may be combined with yet other features or components to form other embodiments. In addition, while a feature of the present invention may have been described in the context of only one of the illustrated embodiments, such feature may be combined with one or more other features of other embodiments, for any given application. It will also be appreciated from the above that the fabrication of the unique structures herein and the operation thereof also constitute methods in accordance with the present invention.

[0062] The preferred embodiment of the present invention has been disclosed. A person of ordinary skill in the art would realize however, that certain modifications would come within the teachings of this invention. It can be further appreciated that functions or structures of a plurality of components or steps may be combined into a single component or step, or the functions or structures of one-step or component may be split among plural steps or components. The present invention contemplates all of these combinations. Unless stated otherwise, dimensions and geometries of the various structures depicted herein are not intended to be restrictive of the invention, and other dimensions or geometries are possible. Plural structural components or steps can be provided by a single integrated structure or step. Alternatively, a single integrated structure or step might be divided into separate plural components or steps. In addition, while a feature of the present invention may have been described in the context of only one of the illustrated embodiments, such feature may be combined with one or more other features of other embodiments, for any given application. It can also be appreciated from the above that the fabrication of the unique structures herein and the operation thereof also constitute methods in accordance with the present invention. The present invention also encompasses intermediate and end products resulting from the practice of the methods herein. The use of "comprising" or "including" also contemplates embodiments that "consist essentially of" or "consist of" the recited feature.

[0063] The explanations and illustrations presented herein are intended to acquaint others skilled in the art with the invention, its principles, and its practical application. Those skilled in the art may adapt and apply the invention in its numerous forms, as may be best suited to the requirements of a particular use. Accordingly, the specific embodiments of the present invention as set forth are not intended as being exhaustive or limiting of the invention. The scope of the invention should, therefore, be determined not with reference to the above description, but should instead be determined with reference to the appended claims, along with the full scope of equivalents to which such claims are entitled. The disclosures of all articles and references, including patent applications and publications, are incorporated by reference for all purposes.

CLAIMS

1. A method of determining position of a target in a three dimensional space comprising:
   i) providing a plurality of base stations;
   ii) determining location of each of the plurality of base stations;
   iii) determining ranges from the target to the plurality of base stations;
   iv) determining height of the target;
   v) selecting ranges from a subset of base stations of the plurality of base stations, wherein the subset of base stations are at a same floor as the target; and
   vi) calculating the position of the target using two dimensional trilateration using the ranges from a subset of base stations and the height of the target.
2. The method of claim 1, wherein the determining the location of at least a portion of the plurality of base stations comprises initializing the plurality of base stations, wherein, during initializing, a first base station of the plurality of base stations sends a signal to a second base station and a third base station of the plurality of base stations to determine a distance between the first base station and the second base station and a distance between the first base station and the third base station and wherein the second base station sends a signal to the third base station to determine a distance between the second base station and the third base station.

3. The method of claim 1, wherein the determining the location of each of the plurality of base stations comprises surveying the plurality of base stations at their locations.

4. The method of claims 1, 2, or 3, wherein the determining the range from the target to the plurality of base stations comprises measuring time of arrival of an at least one signal communicated between the target and the plurality of base stations.

5. The method of claims 1, 2, or 3, wherein the determining the range from the target to the plurality of base stations comprises measuring the time difference of arrival of an at least one signal communicated between the target and the plurality of base stations.

6. The method of claims 1, 2, or 3, wherein the determining the range from the target to the plurality of base stations comprises measuring the received signal strength of at least one signal communicated between the target and the plurality of base stations.

7. The method of claims 1, 2, 3, 4, 5, 6, further comprising associating a floor level with a base station of the plurality of base stations.

8. The method of claims 1, 2, 3, 4, 5, 6, 7, wherein the determining the height of the target comprises measuring the received signal strength of at least one signal communicated between the target and the plurality of base stations.

9. The method of claims 1, 2, 3, 4, 5, 6, 7, wherein the determining the height of the target comprises determining the floor level with the most base stations capable of ranging with the target.

10. A method of determining position of a target in a three dimensional space comprising:

i) providing a plurality of base stations;

ii) determining location of each of the plurality of base stations;

iii) determining ranges from the target to the plurality of base stations;

iv) determining height of the target relative to each of the plurality of base stations;

v) determining projected ranges using the height of the target and the ranges from the target to the plurality of base stations; and

vi) calculating the position of the target using two dimensional trilateration using the projected ranges and the height of the target.

11. The method of claim 10, wherein the determining the location of at least a portion of the plurality of base stations comprises initializing the plurality of base stations, wherein,

during initializing, a first base station of the plurality of base stations sends a signal to a second base station and a third base station of the plurality of base stations to determine a distance between the first base station and the second base station and a distance between the first base station and the third base station and wherein the second base station sends a signal to the third base station to determine a distance between the second base station and the third base station.

12. The method of claim 10, wherein the determining the location of each of the plurality of base stations comprises surveying the plurality of base stations at their locations.

13. The method of claims 10, 11, or 12, wherein the determining the range from the target to the plurality of base stations comprises measuring time of arrival of an at least one signal communicated between the target and the plurality of base stations.

14. The method of claims 10, 11, or 12, wherein the determining the range from the target to the plurality of base stations comprises measuring the time difference of arrival of an at least one signal communicated between the target and the plurality of base stations.

15. The method of claims 10, 11, or 12, wherein the determining the range from the target to the plurality of base stations comprises measuring the received signal strength of at least one signal communicated between the target and the plurality of base stations.

16. The method of claims 10, 11, 12, 13, 14, or 15, further comprising associating a floor level with a base station of the plurality of base stations.

17. The method of claims 10, 11, 12, 13, 14, 15 or 16, wherein the determining the height of the target comprises determining the floor level with the most base stations capable of ranging with the target.

18. The method of claim 10, 11, 12, 13, 14, 15 or 16, wherein the determining the height of the target comprises minimizing the Euclidian norm error of the norm of the grouping of the positions returned from two dimensional trilateration.

19. The method of claim 10, 11, 12, 13, 14, 15 or 16, wherein the determining the height of the target comprises minimizing the averaged square error between the two-dimensional calculated and projected ranges resulting from two-dimensional trilateration between the target and base stations.

20. The method of claim 10, 11, 12, 13, 14, 15 or 16, wherein the determining the height of the target comprises minimizing the averaged square error between the three-dimensional calculated and measured ranges resulting from two-dimensional trilateration between the target and base stations.

21. A method of determining position of a target in a three dimensional space comprising:
    i) providing a plurality of base stations;
    ii) determining location of each of the plurality of base stations;
    iii) determining height of the target;
    iv) determining ranges to a subset of base stations from the plurality of base stations that are at the same floor as the target; and
    v) calculating the position of the target using two dimensional trilateration using the ranges to the subset of base stations and the height of the target.

22. The method of claim 21, wherein the determining the location of at least a portion of the plurality of base stations comprises initializing the plurality of base stations, wherein, during initializing, a first base station of the plurality of base stations sends a signal to a second base station and a third base station of the plurality of base stations to determine a distance between the first base station and the second base station and a distance between the first base station and the third base station and wherein the second base station sends a signal to the third base station to determine a distance between the second base station and the third base station.

23. The method of claim 21, wherein the determining the location of each of the plurality of base stations comprises surveying the plurality of base stations at their locations.

24. The method of claims 21, 22, or 23, wherein the determining ranges to a subset of base stations from the plurality of base stations that are at the same floor as the target comprises measuring time of arrival of an at least one signal communicated between the target and the plurality of base stations.

25. The method of claims 21, 22, or 23, wherein the determining ranges to a subset of base stations from the plurality of base stations that are at the same floor as the target comprises measuring the time difference of arrival of an at least one signal communicated between the target and the plurality of base stations.

26. The method of claims 21, 22, or 23, wherein determining ranges to a subset of base stations from the plurality of base stations that are at the same floor as the target comprises measuring the received signal strength of at least one signal communicated between the target and the plurality of base stations.

27. The method of claims 21, 22, 23, 24, 25, or 26, further comprising associating a floor level with a base station of the plurality of base stations.

28. The method of claims 21, 22, 23, 24, or 25 wherein the determining the height of the target combination thereof.

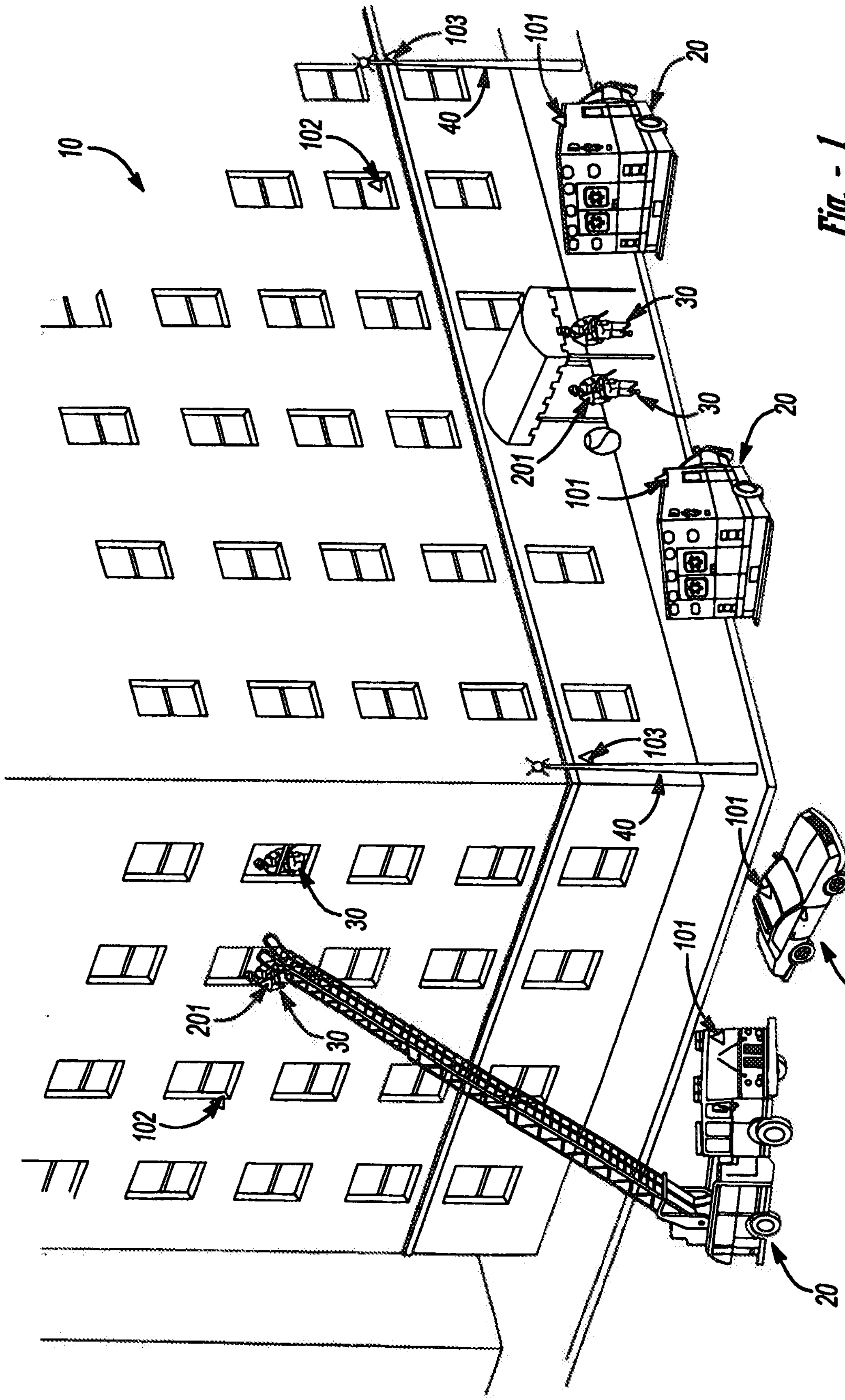


Fig. - 1

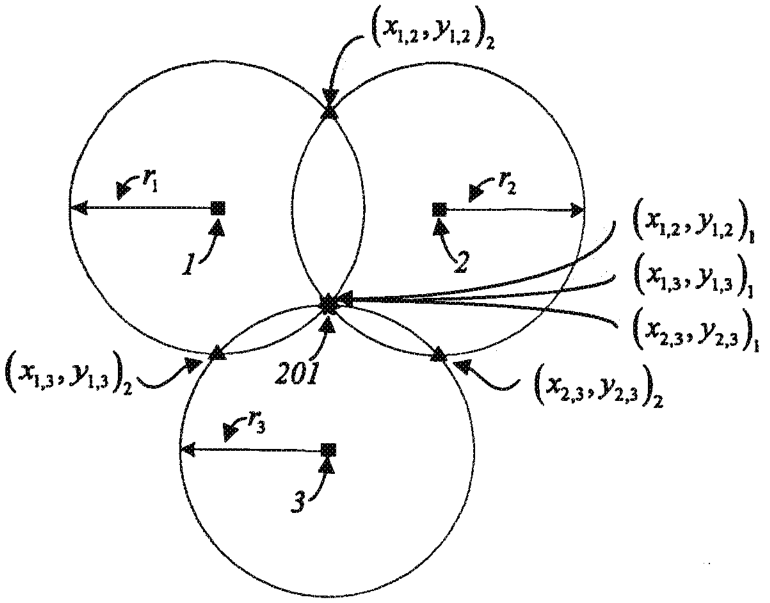

$(x_{1,2}, y_{1,2})_2$
r_1
r_2
1
2
$(x_{1,2}, y_{1,2})_1$
$(x_{1,3}, y_{1,3})_1$
$(x_{2,3}, y_{2,3})_1$
$(x_{1,3}, y_{1,3})_2$
201
$(x_{2,3}, y_{2,3})_2$
r_3
3

Fig. - 2

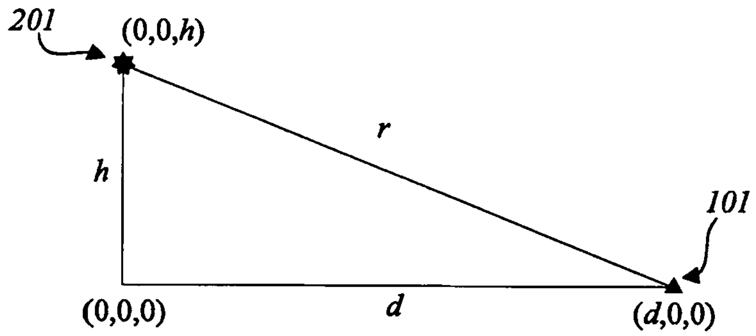


Fig. - 3

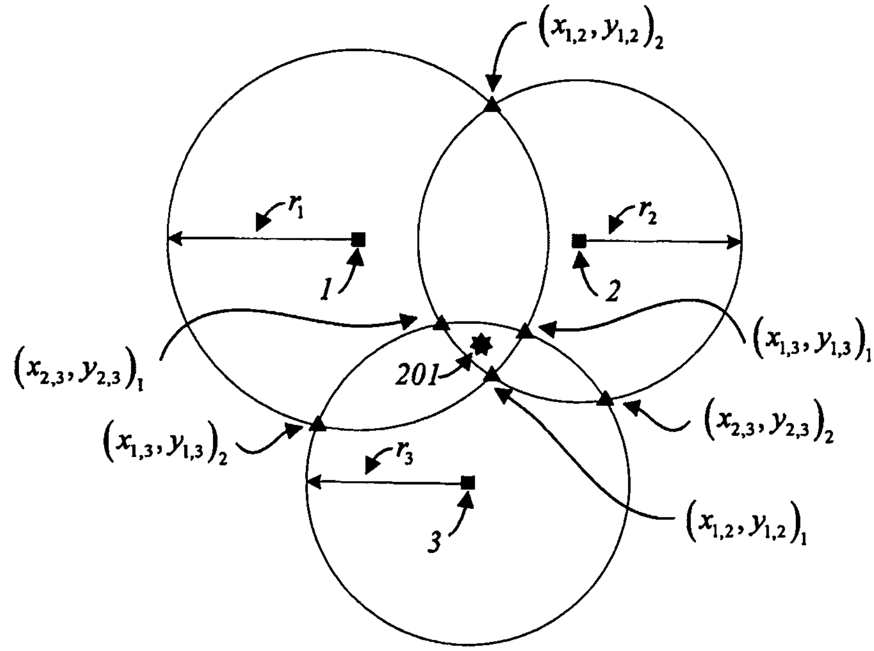

$(x_{1,2}, y_{1,2})_2$
r_1
r_2
1
2
$(x_{2,3}, y_{2,3})_1$
$(x_{1,3}, y_{1,3})_1$
201
$(x_{2,3}, y_{2,3})_2$
$(x_{1,3}, y_{1,3})_2$
r_3
3
$(x_{1,2}, y_{1,2})_1$

Fig. - 4

```
error = infinity
target floor = 0

for floor = 1:max floor
  for base station floor = 1:max floor
    h = | floor height – base station floor height |
      for i = 1:num base stations on base station floor
        d_i = sqrt(r_i^2 - h^2)
        Trilaterate using d_i
  end
  Group
  current error = Euclidean norm of primary grouping
  if current error < error
    error = current error
    target floor = floor
  end
end
```

$$d_i = \sqrt{r_i^2 - h^2}$$

Fig. - 5

```
error = infinity
target floor = 0

for floor = 1:max floor
  for base station floor = 1:max floor
    h = | floor height – base station floor height |
      for i = 1:num base stations on base station floor
        d_i = sqrt(r_i^2 - h^2)
        Trilaterate using d_i
        d̂_i = sqrt((x̂ - x_i)^2 + (ŷ - y_i)^2)
  end
  current error = Σ_{i=1}^{n} (d̂_i - d_i) / n
  if current error < error
     error = current error
     target floor = floor
  end
end
```

$$d_i = \sqrt{r_i^2 - h^2}$$

$$\hat{d}_i = \sqrt{(\hat{x} - x_i)^2 + (\hat{y} - y_i)^2}$$

$$\text{current error} = \sum_{i=1}^{n} \frac{(\hat{d}_i - d_i)}{n}$$

Fig. - 6

error = infinity

target floor = 0

for floor = 1:max floor

for base station floor = 1:max floor

h = | floor height – base station floor height |

for i = 1:num base stations on base station floor

$$d_i = \sqrt{r_i^2 - h^2}$$

Trilaterate using d_i

$$\hat{r}_i = \sqrt{(\hat{x} - x_i)^2 + (\hat{y} - y_i)^2 + (h - z_i)}$$

end

current error = $\sum_{i=1}^{n} \frac{(\hat{r}_i - r_i)}{n}$

if current error < error

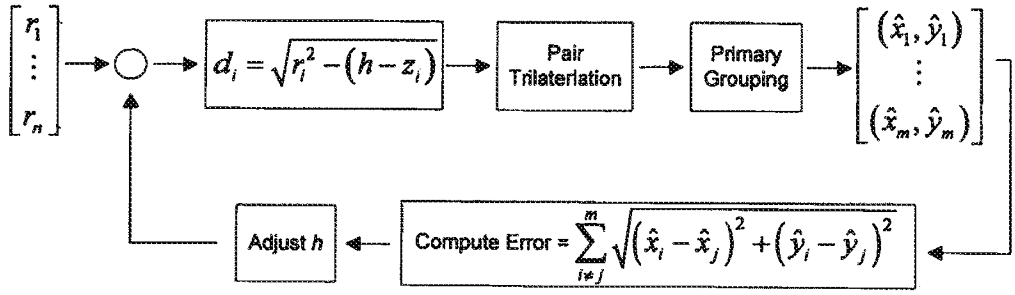
error = current error

target floor = floor

end

end

Fig. - 7



Pair Trilaterlation
Primary Grouping
Adjust h
Compute Error =

Fig. - 8

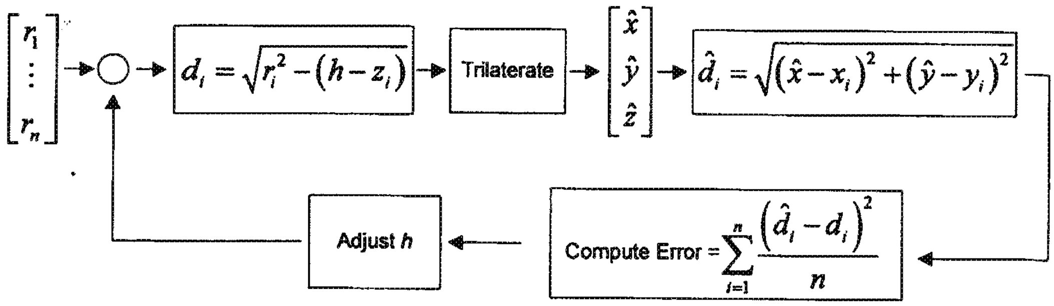

r_1
r_n
$d_i = \sqrt{r_i^2 - (h - z_i)}$
Trilaterate
$\hat{x}$
$\hat{y}$
$\hat{z}$
$\hat{d}_i = \sqrt{(\hat{x} - x_i)^2 + (\hat{y} - y_i)^2}$
Compute Error = $\sum_{i=1}^{n} \frac{(\hat{d}_i - d_i)^2}{n}$
Adjust h

Fig. - 9

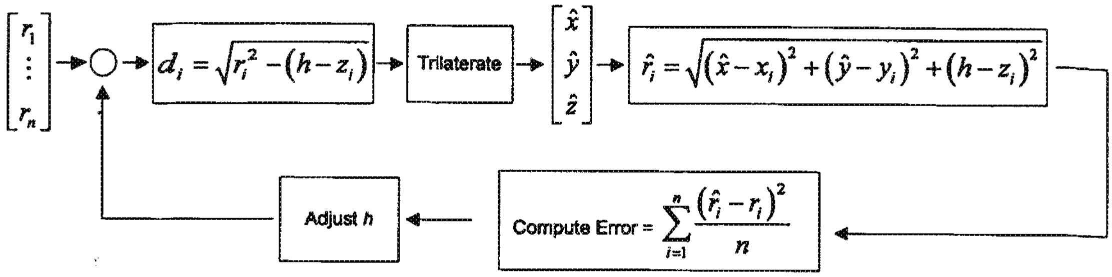

$\begin{bmatrix} r_1 \\ \vdots \\ r_n \end{bmatrix}$
$d_i = \sqrt{r_i^2 - (h - z_i)}$
Trilaterate
$\begin{bmatrix} \hat{x} \\ \hat{y} \\ \hat{z} \end{bmatrix}$
$\hat{r}_i = \sqrt{(\hat{x} - x_i)^2 + (\hat{y} - y_i)^2 + (h - z_i)^2}$
Compute Error = $\sum_{i=1}^{n} \frac{(\hat{r}_i - r_i)^2}{n}$
Adjust h

Fig. - 10