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Weighting fitted method for direction estimation, and apparatus employing the method

Field of the invention

The present invention relates to estimation of the direction from which
5 incoming signals have arrived (so-called "direction of arrival" (DOA)
estimation). In particular, the present invention relates to a method and
apparatus for direction estimation which is based on fitting of the sample
signal power received from a directional antenna. The signal used for the
estimation may be UWB or other signals.

10 Background of Invention

Curve fitting is commonly adopted for curve-estimation based on finite tested
samples. The fitting technique can reduce the effects of discrete samples and
noise to achieve more accurate results. For example, [1] presents 3D shape
15 measurement apparatus using finite probes. In [1], the collected measurement
data are corrected through fitting. In [2,3], Belser presents estimation
methods for the signal peak amplitude and the corresponding instance. His
methods are based on fitting using multiple samples.

20 Fig. 1 illustrates the problem of DOA estimation using conventional fitting-
based techniques. Fig. 1(a) illustrates schematically the apparatus which
solves this problem: a signal receiver has a directional antenna which at any
time "faces" in a given direction. The antenna is in the path of signals (e.g.
UWB signals, or any other form of propagating signals) which are transmitted
25 towards it from a signal direction θ_i . When the sensor faces right to the signal
direction, θ_i , the output magnitude of the sensor should be the maximum. If
the receiving angle is different from θ_i , the sensor output would be smaller.
Specifically, Fig.1 (b) shows the amplitude of the sensor output for each of a

number of possible angles illustrated in Fig. 1(a) in which the sensor may face, and assuming no noise in the system.

To estimate the signal direction of arrival, one conventional direction
 5 estimation method uses an actuator (not shown) to turn the receiver sensor in
 a range of angles, for example $[\theta_L, \theta_R]$, where it is determined in advance that
 the signal direction θ_i is in this range. Assume that in the range $[\theta_L, \theta_R]$ we
 can obtain (receive) N samples at directions θ_1 through θ_N . The signal
 direction of arrival should be around the sample direction at which we receive
 10 the strongest magnitude (or power). However, because the sample directions
 are not continuous and there are environmental noises, the sample direction
 with the strongest power is not exactly the signal direction of arrival. In this
 case, the signal receiver of Fig. 1(a) is designed to perform a fitting technique
 using all the samples within $[\theta_L, \theta_R]$ to estimate the curve in Fig.1 (b), and
 15 thus to obtain the peak of the curve. The direction corresponding to the peak
 would be the DOA.

According to [4], the received signal magnitude, f_s , with respect to the
 direction angle θ can be modelled as a Gaussian function. Let f_s be
 20 described by the Gaussian distribution

$$f_s(\theta) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(\theta-\theta_i)^2}{2\sigma^2}}$$

where σ^2 is the variance. Obviously, to fit this Gaussian function is a
 nonlinear problem. To change it to a polynomial fitting problem, we can pre-
 process the received signal using a logarithmic transform. In [4], the natural
 25 logarithmic transform is employed.

Summary of the invention

The present invention aims to provide a new and useful method for estimation of DOA, as well as apparatus utilizing the method.

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The invention is motivated by the inventors' observation that there is a problem with the estimation technique proposed in [4] and which significantly affects the estimation accuracy. This problem is the SNR of the sample signals. In a conventional fitting algorithm (see [5]), N signal samples in
 10 $[\theta_L, \theta_R]$ are equally weighted. This is not optimal in a noisy environment. Referring to Fig. 2, the line marked "true function" shows the signal amplitude in dB as a function of angle in the absence of noise, while the line marked "received signal" shows a typical actual received signal. The "received signal" has a higher SNR in the central area because the signal is stronger there. On
 15 both the left and right sides, the signal samples would have lower SNR since the signal is weaker. As usual in signal analysis, the higher the SNR of the signal sample, the more stable and reliable it is. A sample with a high SNR could result in more accurate estimation, and it should make a greater contribution to the estimation technique. By contrast, a sample with a low
 20 SNR would be more random, and could lead to bad estimation if too much reliance is placed on it. This sample should make a lower contribution to the estimation.

Accordingly, the present invention proposes in general terms that the
 25 conventional fitting method is modified to employ a weighted fitting estimator. That is, the estimate of the DOA is performed based on a mathematical function in which logarithmic power amplitudes from respective samples are weighted by respective weight values. This makes more efficient use of the received signal samples.

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The weight values may simply be the amplitudes themselves (optionally, normalised) since, as discussed above, the amplitudes are well correlated with high values of SNR. Alternatively, the weight values may not just be functions of the respective signal amplitudes. For example, they may be a function of (e.g. proportional to) the gain function of the antenna at the corresponding angle.

Compared with the conventional fitting for DOA estimation, embodiments of the present invention may have the following advantages:

- 10 1: More efficient use of sample data.
- 2: Higher estimation accuracy.

These two advantages may be achieved, using the invention, with an algorithm having a similar complexity to the conventional one.

One specific expression of the invention is a method of estimation of a direction of arrival of a signal using a directional antenna, the antenna having an axis which can be moved through a range of angles and having a maximum sensitivity to signals received parallel to said axis, the method including the steps of:

- (a) obtaining, for each of a plurality of angular positions θ_k of the axis of the said antenna, a respective signal strength sample value $p(\theta_k)$;
- (b) using the sample values $p(\theta_k)$ and/or the value of a gain function of the directional antenna at the corresponding angle θ_k to obtain, for each sample value, a respective weight value w_k ; and
- (c) obtaining indication values indicative of an estimate of the direction of arrival from a mathematical function including a respective logarithm value of each sample value, each said logarithm value being weighted in the mathematical function by the respective weight value.

Note that optionally, there may be more than one sample value for each particular angular position.

The invention may alternatively be expressed as a direction of arrival estimation apparatus arranged to perform the method as expressed above.

- 5 Furthermore, the direction of arrival estimation apparatus may be part of a position estimation apparatus, in which the position of the apparatus (e.g. location within a two-dimensional space) is determined by (a) obtaining the estimated DOAs of two or more signals and (in the "reference-free" case that the apparatus does not employ prior knowledge about the absolute locations
10 or positional relationships of the objects which transmitted the signals towards the apparatus) the respective distances of the objects which transmitted the signals towards the apparatus, and (b) performing a triangulation using the multiple DOAs to obtain an estimated position. Optionally, the apparatus may include means for generating a signal which is transmitted in all directions,
15 and the directional antenna may be used to receive reflected signals from reflective objects, and obtain the DOA of each reflective object. Distances to these objects may be obtained using reflection delays.

Brief Description of The Figures

Preferred features of the invention will now be described, for the sake of
20 illustration only, with reference to the following figures in which:

Fig.1, which is composed of Fig. 1(a) and Fig. 1(b), illustrates the archetypical problem of fitting-based direction estimation, and the relationship between signal magnitude and direction angle for a directional sensor;

Fig. 2 illustrates the noise-free signal power (in dB) and the real
25 received power (in dB, signal + noise) versus direction angles;

Figs. 3 to 5 show the simulated MSE versus SNR performance of an estimation approach which is an embodiment of the present invention, as

compared with a prior art technique, for different angle ranges and different sample step-sizes;

Fig. 6 shows the experimental UWB reflection signals received by a directional antenna in various directions; and

5 Fig. 7 is a schematic representation of an apparatus which is an embodiment of the invention.

Detailed Description of the embodiments

10 A DOA technique which is an embodiment of the invention will now be described. The construction of the embodiment is once more that illustrated in Fig. 1(a) – although as explained below the operation of the signal receiver is different in detail. Once more, the actual signal received, and on which the embodiment operates, is that shown as "Received signal" in Fig. 2. The signal
15 which would be received in the absence of noise (i.e. the one shown in Fig. 1(b)) is denoted here by f_s , and is stained by the additive white Gaussian noise (AWGN) $n(\theta)$. Therefore the received signal $f_r(\theta)$ can be represented as

$$20 \quad f_r(\theta) = f_s(\theta) + n(\theta)$$

Following [4], we first change the non-linear function to a polynomial by a logarithmic transform. Any of a number of transforms can be used within the scope of the invention, but for easy understanding we just adopt "dB" in the
25 following explanation. The actual received signal in dB (i.e. the "received signal in Fig. 2), dp_r , is represented as

$$dp_r(\theta) = 20 \log f_r(\theta) = 20 \log [f_s(\theta) + n(\theta)]$$

On the other hand the signal power dp_s in dB (i.e. the "true function" of Fig. 2), should be

$$\begin{aligned}
 dp_s(\theta) &= 20 \log f_s(\theta) \\
 &= 20 \log \left(\frac{1}{\sqrt{2\pi}\sigma} \right) - \frac{(\theta - \theta_0)^2}{\sigma^2} \log(e) \\
 &= \frac{-\log(e)}{\sigma^2} (\theta^2 - 2\theta_0\theta + \theta_0^2) + 20 \log \left(\frac{1}{\sqrt{2\pi}\sigma} \right) \\
 &= a\theta^2 + b\theta + c
 \end{aligned}$$

where

$$\begin{cases} a = -\log(e) \cdot \frac{10}{\sigma^2} \\ b = +\log(e) \cdot \frac{2\theta_0}{\sigma^2} \\ c = \frac{-\log(e)}{\sigma^2} \theta_0^2 + 20 \log \left(\frac{1}{\sqrt{2\pi}\sigma} \right) \end{cases}$$

As can be seen, dp_s is an exact second-order polynomial formula (i.e. the "true function" in Fig. 2 is a parabola). However, because of the additive noise, the received samples actually are realised as the "received signal". We can use second-order polynomial fitting to estimate the unknown parameters: a, b, c . After that the DOA estimation would be a simple function of these parameters.

One conventional polynomial fitting algorithm can be stated as,

- 1). Calculate $\bar{\theta}_i = \frac{1}{i} \sum_{k=1}^i \theta_k$ and $d\bar{p}_i = \frac{1}{i} \sum_{k=1}^i dp(\theta_k)$, where θ_k is the direction angle at which the sample k is received ($\theta_L \leq \theta_k \leq \theta_R$), $dp(\theta_k)$ is the corresponding power in dB of the received signal.
- 2). The parameter estimation output is

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$$\begin{bmatrix} \hat{a} \\ \hat{b} \\ \hat{c} \end{bmatrix} = (A^T A)^{-1} A^T Y$$

where

$$A = \begin{bmatrix} \bar{\theta}_1^2 & \bar{\theta}_1 & 1 \\ \bar{\theta}_2^2 & \bar{\theta}_2 & 1 \\ \dots & \dots & \dots \\ \bar{\theta}_N^2 & \bar{\theta}_N & 1 \end{bmatrix}, \quad Y = \begin{bmatrix} d\bar{p}_1 \\ d\bar{p}_2 \\ \dots \\ d\bar{p}_N \end{bmatrix}$$

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- 3). The estimated signal DOA is $\hat{\theta}_i = \frac{-\hat{b}}{2\hat{a}}$

We can see, in calculating $\bar{\theta}_i$ and $d\bar{p}_i$ in the conventional fitting, all signal samples have the same weight, although these samples have different SNR.

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By contrast, the embodiment operates as follows. To make use of these signal samples more efficiently, the embodiment adopts different weights in terms of SNR. Since the white noise has constant statistical strength in all directions, the weighting in terms of SNR is approximately equal to the weighting in terms of signal strength, which is simpler in practical operations. Accordingly, the embodiment has the following steps:

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- 1) Derive a weight for each signal sample. The weight may be determined as

$$w_i = p_r(\theta_i) / [p_r(\theta_1) + \dots + p_r(\theta_N)],$$

where p_r is the received power (before logarithmic transform).

5 2) Calculate $\bar{\theta}'_i = \frac{1}{i} \sum_{k=1}^i w_k \theta_k$ and $d\bar{p}'_i = \frac{1}{i} \sum_{k=1}^i w_k dp(\theta_k)$.

3) Estimate parameters a, b, c from the following equations:

$$\begin{bmatrix} \hat{a} \\ \hat{b} \\ \hat{c} \end{bmatrix} = (A'^T A')^{-1} A'^T Y'$$

10 where

$$A' = \begin{bmatrix} \bar{\theta}'_1{}^2 & \bar{\theta}'_1 & 1 \\ \bar{\theta}'_2{}^2 & \bar{\theta}'_2 & 1 \\ \dots & \dots & \dots \\ \bar{\theta}'_N{}^2 & \bar{\theta}'_N & 1 \end{bmatrix}, \quad Y' = \begin{bmatrix} d\bar{p}'_1 \\ d\bar{p}'_2 \\ \dots \\ d\bar{p}'_N \end{bmatrix}$$

4). The output direction estimation is $\hat{\theta}_i = \frac{-\hat{b}}{2\hat{a}}$

15 To verify the performance of the direction estimation, the second-order polynomial weighed fitting is simulated and experimentally tested. The simulated results are shown in Fig.3 through Fig.5. The experimental signals are shown in Fig.6, and the processing results are given in Table1.

20 Fig.3 shows the mean squared error (MSE) versus SNR of the direction estimation using the embodiment as compared with the prior art fitting method

described above. The MSE here is defined as $MSE = E\left(\left|\frac{\hat{\theta}_0 - \theta_0}{360}\right|^2\right)$; the

direction angle range is [20, 160]; the direction sample step-size is 10 degrees. We can see the embodiment outperforms the prior art method very much in this case.

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Fig.4. shows the MSE performance of the weighted fitting approach in a smaller directional angle range: [50, 130]. The directional sample step-size is still 10 degrees. We can see that the difference between the embodiment and prior art method becomes smaller if the sample directional range is reduced.

10 This is reasonable because the scan sample range concentrates to the central area, the SNR difference would become small. However, the embodiment is still better than the prior art method.

Fig.5. shows the MSE in the scan direction angular range: [50, 130] in
15 direction sample step-size of 2 degrees. This means the samples are denser in the same range as in Fig.4. We can see the fitting performance is improved for both the embodiment and prior art method. However, the factor of improvement for the embodiment is bigger.

20 Fig. 6 shows experimental results using received UWB signal samples reflected from a 1.2 meter distance wall. We repeated the scanning from 10 degrees to 170 degrees 30 times to obtain the standard deviation (STD).

Table 1 shows the experiment performance of the embodiment compared with
25 the prior art method. In each column the top entry is the scanning range, the middle column is the STD entry for the prior art, and the lower entry is the STD for the embodiment. The step size in each case is 10 degrees. We can see the embodiment can achieve 1.564 degrees accuracy, while the prior art

one only 3.3 degrees accuracy, as indicated by the values marked with an asterisk in Table. 1.

Angle range (degrees)	10~170	20~160	30~150	40~140	50~130	60~120	70~110
STD for prior art method	140.450	25.165	29.165	7.4387	3.3236*	5.7918	135.827
STD for embodiment	1.7490	1.5646*	1.5968	1.6908	1.7493	2.1831	20.0531

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Table 1

In summary, the embodiment improves the direction estimation accuracy, compared to the prior art technique. If such a method is improved within a positioning system which estimates the position of the signal receiver using incoming signals from two (or more) directions, the positioning accuracy will be higher than in a system employing the prior art method.

Fig. 7 shows the overall structure of a positioning system which is a possible embodiment of the invention. It includes an antenna 1, an actuator 2 for moving the antenna, and a signal receiver 3. The signal receiver 3 includes a first processor 5 for performing a method as described above to obtain successively a DOA for two signals received from different directions (the system may be able to distinguish them based on their different characteristics, such as different frequencies), and a second processor 7 for controlling the actuator 2 (e.g. to scan respective ranges of angles for each of

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the signals) and the processing unit 5. The second processor 7 uses the DOAs obtained by the first processing unit 5 to obtain a position estimate by triangulation, according to conventional methods. Of course, in practice the processors 5 and 7 may be simply different software modules operating on a
 5 single physical processor.

Although only a single embodiment of the invention has been described in detail, various modifications are possible within the scope of the invention as will be clear to a skilled reader. For example, the weights may be chosen
 10 according to a different algorithm. In another example, following a first use of the algorithm to form an estimate of the DOA, the weights may be re-derived using the estimated DOA (for example, by setting to zero all weights in respect of directions far away from the estimated DOA), and the algorithm performed again to obtain a better estimate of the DOA.

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In another important variation, the weight values ω_k are chosen as a function of (e.g. proportional to) the gain function of the antenna at the corresponding angle θ_k . For example, if the gain is written as $B(\theta_k - \theta_M)$, where θ_M is the angle for which B is maximal (i.e. $B(0)$ is the maximal gain), then the weights
 20 may be chosen as $\omega_k = B(\theta_k - \theta_M)$. Steps (1) to (4) of the embodiment described above may be performed with these weight values.

In other embodiments the weight values may be formed using both the corresponding value of the gain function and the corresponding sample value,
 25 e.g. as the product of the two.

In a further variation, the weighted fitting can be used in peak time estimation by fitting in the time domain of sample values measured at respective instants

to a pulse shape. This may, for example, allow a determination of the distances to the objects which transmitted the signals.

In a further possible variation, the antenna may receive signals from any
 5 direction within a three-dimensional space, so that the DOA of a given signal is defined by two angles, not one. The techniques proposed above may be extended straightforwardly to this situation, which may for example be used for position finding within a three-dimensional space.

10 References

The disclosure of the following references is incorporated by reference.

- [1]. Ohtsuka; Masaru, "Apparatus and method for measuring a shape using multiple probes." US patent No. 6,701,633, March 9, 2004.
- 15 [2]. Belser; Karl A., "Disk drive system having hybrid analog/digital pulse peak instance/amplitude data detection channels." US patent 6185174. Aug. 1998.
- [3] Belser; Karl A., "Detection of pulse peak instance and amplitude in a storage drive. " US patent 6529490. Jan.1999.
- [4] Henry E. Lee, "Target Angle Estimation for Search Radar." US patent
 20 6201496. Mar. 2001.
- [5] <http://mathworld.wolfram.com>

Claims

1. A method of estimation of a direction of arrival of a signal using a directional antenna, the antenna having an axis which can be moved through a range of angles and having a maximum sensitivity to signals received parallel to said axis, the method including the steps of:
 - (a) obtaining, for each of a plurality of angular positions θ_k of the axis of the said antenna, a respective signal strength sample value $p(\theta_k)$;
 - (b) using the sample values $p(\theta_k)$ and/or the value of a gain function of the directional antenna at the corresponding angle θ_k to obtain, for each sample value, a respective weight value w_k ;
 - (c) obtaining indication values indicative of an estimate of the direction of arrival from a mathematical function including a respective logarithm value of each sample value, each said logarithm value being weighted in the mathematical function by the respective weight value.
2. A method according to claim 1 in which the weight values w_k are proportional to the respective sample values.
3. A method according to claim 2 in which the weight value w_k for each respective sample value is equal to the sample value divided by the sum of the sample values.
4. A method according to claim 1 in which the weight values are proportional to the gain function $B(\theta_k - \theta_M)$ of the directional antenna at the corresponding angle θ_k , where θ_M is the angle for which B is maximal.
5. A method according to claim 3 or claim 4 in which step (c) includes:

(i) calculating the weighted average angle $\bar{\theta}_i' = \frac{1}{i} \sum_{k=1}^i w_k \theta_k$ and weighted average sample power in dB $d\bar{p}_i' = \frac{1}{i} \sum_{k=1}^i w_k dp(\theta_k)$; and

(ii) obtaining said indication values $\hat{a}, \hat{b}, \hat{c}$ as given by:

$$\begin{bmatrix} \hat{a} \\ \hat{b} \\ \hat{c} \end{bmatrix} = (A'^T A')^{-1} A'^T Y'$$

5 where

$$A' = \begin{bmatrix} \bar{\theta}_1'^2 & \bar{\theta}_1' & 1 \\ \bar{\theta}_2'^2 & \bar{\theta}_2' & 1 \\ \dots & \dots & \dots \\ \bar{\theta}_N'^2 & \bar{\theta}_N' & 1 \end{bmatrix}, \quad Y' = \begin{bmatrix} d\bar{p}_1' \\ d\bar{p}_2' \\ \dots \\ d\bar{p}_N' \end{bmatrix},$$

said estimated direction being given by

$$\hat{\theta}_0 = \frac{-\hat{b}}{2\hat{a}}.$$

10 6. Apparatus for estimating the direction of arrival of a signal, the apparatus comprising:

a directional antenna, the antenna having an axis having a maximum sensitivity to signals received parallel to said axis;

an actuator for moving the antenna through a range of angles; and

15 a processor arranged to receive from the antenna, for each of a plurality of angular positions θ_k of the axis of the said antenna, a respective signal strength sample value $p(\theta_k)$;

said processor being arranged to:

(a) use the sample values $p(\theta_k)$ and/or the value of a gain function of the directional antenna at the corresponding angle θ_k to obtain, for each sample value, a respective weight value w_k ;

(b) obtain indication values indicative of an estimate of the direction of arrival from a mathematical function including a respective logarithm value of each sample value, each said logarithm value being weighted in the mathematical function by the respective weight value; and

(c) obtain said estimate of the direction of arrival from said indication values.

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7. An apparatus according to claim 6 in which the weight values w_k are proportional to the respective sample values.

8. An apparatus according to claim 7 in which the weight value w_k for each respective sample value is equal to the sample value divided by the sum of the sample values.

9. A method according to claim 6 in which the weight values are proportional to the gain function $B(\theta_k - \theta_M)$ of the directional antenna at the corresponding angle θ_k , where θ_M is the angle for which B is maximal.

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10. An apparatus according to claim 8 or claim 9 in which the processor is arranged to obtain the indication values by:

(i) calculating the weighted average angle $\bar{\theta}_i' = \frac{1}{i} \sum_{k=1}^i w_k \theta_k$ and weighted

25 average sample power in dB $\bar{dp}_i' = \frac{1}{i} \sum_{k=1}^i w_k dp(\theta_k)$; and

(ii) obtaining said indication values $\hat{a}, \hat{b}, \hat{c}$ as given by:

$$\begin{bmatrix} \hat{a} \\ \hat{b} \\ \hat{c} \end{bmatrix} = (A'^T A')^{-1} A'^T Y'$$

where

$$5 \quad A' = \begin{bmatrix} \bar{\theta}_1'^2 & \bar{\theta}_1' & 1 \\ \bar{\theta}_2'^2 & \bar{\theta}_2' & 1 \\ \dots & \dots & \dots \\ \bar{\theta}_N'^2 & \bar{\theta}_N' & 1 \end{bmatrix}, \quad Y' = \begin{bmatrix} d\bar{p}_1' \\ d\bar{p}_2' \\ \dots \\ d\bar{p}_N' \end{bmatrix},$$

the processor being arranged to obtain said estimated direction of arrival from the formula

$$\hat{\theta}_0 = \frac{-\hat{b}}{2\hat{a}}.$$

11. A positioning system including a direction estimation apparatus
 10 according to any of claims 6 to 10, and further including a second processor for controlling the direction estimation apparatus to obtain a direction of arrival estimation for each of at least two received signals, and for using said at least two direction of arrival estimations to obtain an estimate of a location of the positioning system.