DETECTION AND COMPENSATION OF SENSOR MALFUNCTION IN TIME DELAY BASED DIRECTION OF ARRIVAL ESTIMATION

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ABSTRACT

There is an increasing need for robust localization of signal sources of various types. With recent developments in sensory instrumentation, some of these needs can be answered. These new developments have also introduced new requirements. Sensor arrays and networks operate for long periods of time, perhaps unattended, and hardware malfunctions may occur between scheduled maintenance. Sensor systems should be able to detect and compensate for hardware failures. This paper presents a new method to detect and compensate for a failure of one sensor in an array performing time delay based direction of arrival (DOA) estimation. The method utilizes confidence factors based on the planar wave assumption. The proposed method is combined with time delay based DOA estimators and tested with simulations. Results indicate that the given method can be used to detect the failed sensor and improve DOA estimation performance when a failure has occurred.

1. INTRODUCTION

A variety of events and sources emit information that is transmitted as propagating waves. A significant amount of research work has been devoted to extracting information from these waves using sensor arrays [1]. There are many applications for sensor arrays [2], including acoustic applications with microphones [3], seismic measurements, medical devices, telecommunications and, more recently, passive surveillance of large areas [4].

There are various reasons for increasing interest in sensor arrays. Firstly, sensory instruments and processors are becoming cheaper and more capable. In addition, these devices consume less power and battery capacities are increasing. Secondly, the number of sensors in systems is increasing, and these systems are operating as an interconnected network. Also, the deployment of sensor systems is becoming automated.

Because of these developments, sensor systems are expected to operate for long periods of time — unattended. This introduces a new kind of requirement for sensor arrays. Robustness should be considered with higher emphasis, since prolonged operation increases the probability of failures between scheduled maintenance. Hardware failures may also occur when an automatic or semi-automatic system is used for deployment.

A sensor system should be able to diagnose its performance and detect possible malfunctions. This information is vital to the user of the data to avoid incorrect conclusions and decisions based on unreliable information. Furthermore, an intelligent sensor system should compensate for some failures, such as the failure of one sensor in the array. This paper addresses the problems caused by a sensor failure in an array used for time delay based direction of arrival (DOA) estimation. We present a new method for detecting and compensating for the failure of one sensor in an array. The detection is based on the planar wave assumption, which can be used to form confidence factors [5] for time delays. Using these confidence factors we determine if one of the sensors in the array is producing improper data and has failed. After detection, all data from the failed sensor are discarded and DOA is computed without these data. The performance of the method is demonstrated with simulations, in which the proposed method is combined with typical time delay based based DOA estimators.

[*]Author is visiting ICSI from TUT until August 2004.

2. DIRECTION OF ARRIVAL ESTIMATION

The problem of time delay estimation (TDE) has been extensively studied [6], and several estimators [7] are available. The actual process of time delay estimation is beyond the scope of this paper, but it should be noted that there exists no single estimator that is suitable for all TDE scenarios [1]. It should also be noted that the TDE performance and distribution depend on the chosen estimator as well as signal and noise characteristics, and thus affect the output of a time delay based DOA estimator.

There are various methods for estimating DOA, and source localization from time delays is a well studied problem. Many different approaches exist for a direct solution [5, 8, 9, 10]. For reference, we now give briefly the basic method of estimating DOA from time delays [8]. Consider two spatially separated sensors, indexed by natural numbers i and j. When a planar wave passes these sensors, a time delay is generated between these sensors according to [2]

$$\tau_{(i,j)} = \boldsymbol{x}_{(i,j)} \cdot \boldsymbol{k} \tag{1}$$

where $\tau_{(i,j)}$ is the time delay between the *sensor pair* (i, j), $\boldsymbol{x}_{(i,j)}$ is the *sensor vector* from sensor i to sensor j and $\boldsymbol{k}$ is the propagation vector [11] of the planar wave. The propagation vector has the direction of wave propagation and norm (L_2) equal to the inverse of propagation speed.

In an array of N sensors there are $(N^2 - N)/2$ distinct sensor pairs. All satistfy Eqn. (1), and we can group all pairwise equations into matrix form

$$\begin{bmatrix} \tau_{(1,2)} \\ \tau_{(1,3)} \\ \tau_{(1,4)} \\ \vdots \\ \tau_{(M-1,M)} \end{bmatrix} = \begin{bmatrix} \boldsymbol{x}^T_{(1,2)} \\ \boldsymbol{x}^T_{(1,3)} \\ \boldsymbol{x}^T_{(1,4)} \\ \vdots \\ \boldsymbol{x}^T_{(M-1,M)} \end{bmatrix} \boldsymbol{k} \quad \Leftrightarrow \quad \boldsymbol{\tau} = \boldsymbol{X}\boldsymbol{k} \quad (2)$$

If time delays are known or estimated, the propagation vector can be solved from Eqn. (2) with least squares pseudoinverse [8]

$$\hat{\boldsymbol{k}} = \left(\boldsymbol{X}^T\boldsymbol{X}\right)^{-1}\boldsymbol{X}^T\hat{\boldsymbol{\tau}} \quad (3)$$

There are also other methods for solving the propagation vector from time delays, such as averaging within subarrays [9], the grid search with MAD-solution (and its computationally reduced version) [12]. Also LS-solution with weighting [10] for the unit norm solution (norm of propagation vector is assumed unity) has been proposed. All these methods aim to minimize small errors in time delays (e.g. quantization) but are ineffective when one or more of time delays contain large errors, a situation likely to occur if one of the sensors is not functioning properly.

3. PROPOSED METHOD

This section describes the proposed method for detecting sensor failures. While reading this section, the reader may find it convenient to refer to Table 1 summarizing the method.

When one of the sensors in an array fails and starts to produce improper data, the time delays related to this sensor become erroneous, and thus introduce errors into the DOA estimates. A brief analysis of these errors can be found in [13]. It is assumed that the malfunction is not trivial to detect, such as a sensor giving no signal at all, but that the sensor is still producing signals, which may even be partially correct.

Time delays can be checked for errors using the triangularity condition and confidence factors that have been used for DOA estimate optimization by time delay selection [5]. This selection method is not optimized for failure situations. However, the confidence factors utilized in selection are also a powerful tool for failure detection.

The triangularity condition arises from the planar wave assumption. Taking any three sensors i, j and l in an array, and forming pairs, the sensor vectors between these pairs form a triangle

$$\boldsymbol{x}_{(i,j)} + \boldsymbol{x}_{(j,l)} - \boldsymbol{x}_{(i,l)} = 0 \quad (4)$$

In fact, this zero sum condition is valid for all closed sensor vector paths in an array, but for our purposes it is sufficient to use triangles with three distinct sensor vectors. From Eqn. (1) and the zero sum condition of Eqn. (4) it follows (assuming $\boldsymbol{k} \neq \boldsymbol{0}$) that

$$\tau_{(i,j)} + \tau_{(j,l)} - \tau_{(i,l)} = 0 \quad (5)$$

Therefore, the time delay estimates in the triangle $\{i, j, l\}$ can be tested for errors by thresholding [5]

$$\Delta_{(i,j,l)} = \begin{cases} 1 \;, & \left|\, \hat{\tau}_{(i,j)} + \hat{\tau}_{(j,l)} - \hat{\tau}_{(i,l)} \,\right| < D_{(i,j,l)} \\ 0 \;, & \text{otherwise} \end{cases} \quad (6)$$

where $D_{(i,j,l)}$ is the threshold value adjusted by the norm of maximum tolerable error, as explained in [5]. To obtain a confidence factor for a single time delay, the triangular tests are summed over all triangles into which the time delay belongs:

$$\Upsilon(i,j) = \sum_{l \in \mathcal{X} - \{i,j\}} \Delta_{(i,j,l)} \quad (7)$$

where $\mathcal{X}$ is the set of all sensor indices. Finally, to determine the reliability of each sensor in the array, the confidence factors of time delays connected to a selected sensor are grouped. Thus, for sensor i we have a set of confidence factors

$$S_i = \{\Upsilon(i,j) \mid j \in \mathcal{X} - \{i\}\ \} \quad (8)$$

If a sensor has failed, all of its time delays should be corrupted and have zero confidence factors. Thus, to detect a failure, we are searching for a sensor index i for the set S_i with all zero members. These indices are searched from each time frame to form a sequence of failure indicators

$$\upsilon(n) = \begin{cases} i \;, & \exists!\, i : \ (\forall s \in S_i : s = 0) \\ 0 \;, & \text{otherwise} \end{cases} \quad (9)$$

where S_i is the set of confidence factors for sensor i at time instant n. If there are no sets S_i whose all members are zero, or there are several (and $\upsilon(n) = i$ is not unique), $\upsilon(n)$ is set to zero.

Since the failed sensor produces random time delays, it may occasionally happen that some of them pass the triangularity test of Eqn. (6). Thus, there may be time instants when the confidence set of a failed sensor is not all zeros. In addition, it may also happen (due to noise) that time delays from one of the properly operating sensors do not pass the triangularity test. As a consequence, there may be time instants when a properly operating sensor has an all zeros confidence set. Due to this randomness, detection of a failed sensor can not be based on confidence information from a single time delay frame. Rather, consecutive time frames must be used. This makes the detection possible also when no (planar wave) source signal is present and time delays pass the triangularity test randomly.

To detect the failed sensor, past values of the sequence of failure indicators are monitored. If D_{fail} or more out of B previous values are the same sensor index, it can be decided that a failure has occurred. To avoid ambiquities, threshold should be chosen to satisfy $D_{fail} > B/2$. The length of the buffer and threshold can be selected depending on requirements on detection sensitivity, possibility of false detection, and delay time from failure to detection. In our experiments, relatively small values of $B = 9$ and $D_{fail} = 5$ were used.

After the failure threshold D_{fail} has been exceeded, the detection result remains and is changed only if some other sensor exceeds the threshold. If zero entries dominate the buffer some time after the failure detection, the detection result is not reverted to proper operation. The proposed detection algorithm is summarized in Table 1.

After a sensor failure is detected, all sensor vectors and time delays connected to the failed sensor are discarded from the propagation vector estimation in Eqn. (3). Depending on the number of sensors and array geometry, it may happen that the remaining sensors do not constitute a three dimensional array. In such cases only two dimensional propagation vector estimation is possible. If the propagation speed of the planar wave is known, it can be used to find the absolute value of the third component. However, some ambiquity remains in such cases.

1. Estimate time delays from all sensor pairs.
2. Test all sensor pair triangles with Eqn. (6)
3. Compute confidence factors for all time delays (Eqn. (7)) and generate sets S_i for all sensors (Eqn.(8)).
4. Is there an unique sensor i whose set S_i is all zeros?

   Yes: Set $\upsilon(n) = i$.

   No: Set $\upsilon(n) = 0$, and move to step 6.
5. Are there D_{fail} or more entries from a single sensor i in the past B values of $\upsilon(n)$?

   Yes: Change detection result to "failure in sensor i".

   No: Keep the previous detection result.
6. Advance to the next time frame and return to step 1

Table 1. Proposed algorithm for detecting sensor failure.

4. SIMULATIONS

The proposed method was tested by simulating sensor failure in the presence of a signal source. Simulations were conducted using an array of eight senors located at apices of a cube. The length of the base of the cube was equal to a distance travelled by a propagating wave in nine samples. This corresponds e.g. to a 0.31 m cube with 10 kHz sampling rate and $c = 343\ \frac{\text{m}}{\text{s}}$. Simulations consisted of 20000 DOA estimation runs with 1000 time delay frames in each run. The time delays were generated using a random model for source movement in azimuth-elevation space:

$$\theta(n) = \theta(n-1) + 5\cos(\rho(n)) \quad (10)$$

$$\phi(n) = \phi(n-1) + \frac{5}{4}\sin(\rho(n)) \quad (11)$$

where $\theta(n)$ is the azimuth and $\phi(n)$ is the elevation at time instant n. Angle $\rho(n)$ is the direction of movement in the azimuth-elevation space, and it was generated by the random process

$$\rho(n) = \rho(n-1) + u(n) \quad (12)$$

where $u(n)$ is random and white on the interval $[-\pi/4, \pi/4]$. The failure of a single sensor occurred in each simulation run with probability $1/2$. The failing sensor was selected randomly out of all sensors in the array. The time of failure was also selceted randomly. However, it was limited *not* to occur in the first or last 9 samples of each run to avoid problems arising from lack of data before or after the failure. This is a neglible limitation, since in practical situations data is available before and after the sensor failure. Time delays were generated using Eqn. (2) and quantized to nearest values allowed by the sampling rate. Although various interpolation strategies can be used to improve the accuracy of time delay estimation in appropriate conditions, the time delay generation was limited in this simulation to sample accuracy for the following reasons: The quantization error can be used to take into account the errors that may occur in time delay estimation process. These errors can be caused by disturbing noise, wavefronts which are not perfectly planar, and source movement within the time delay estimation frame. Furthermore, it would not be realistic to assume that time delays can be estimated with near-perfect precision, even if interpolation is used. In addition, exact modelling of the output distribution of the time delay estimator would require restricting assumptions on the choice of the estimator as well as source and noise signals.

After time delay generation and quantization, uniformly distributed quantized noise on the interval $[-2, 2]$ was added to each time delay to take into account the possibility of errors when there are no sensor malfunctions. If the absolute value of the resulting time delay was larger than τ_{MAX}, the maximum time delay for the sensor pair being processed, the noisy time delay was aliased back to the interval $[-\tau_{MAX}, \tau_{MAX}]$. This was done in order to avoid the occurrence of impossible values for time delays.

After the sensor failure occurred, time delays connected to the failed sensor were generated using a three state process with states for correct, random and three-point time delay generation. These were used to take into account the typical behavior of a failed device, when signals, in addition to being partially correct, include electrical noise with strong periodic components. State transitions occurred after each time frame, with transition probability $1/2$ for keeping the current state and $1/4$ for changing to one of the two other states. The correct state generated time delays as if the sensor was operating without failure. The random state selected any of the possible values with equal probability. The three-point model selected the time delay randomly from the set $\{-\tau_{MAX}, 0, \tau_{MAX}\}$. Probabilities for these were $P(\tau_{MAX}) = P(-\tau_{MAX}) = 1/4$ and $P(0) = 2P(\tau_{MAX}) = 1/2$.

5. RESULTS AND DISCUSSION

Propagation vectors were estimated from the generated time delays using the least squares solution (LS) of Eqn. (3), averaging with subarrays (AVG) [9] and their combinations with the proposed failure detection and compensation method. LS-solution without the failure effects was used as the reference. Detection buffer length was $B = 9$ and threshold values in detection were $D_{fail} = 5$ and $D_{(i,j,l)} = 1/(20c)$. With these settings, the proposed detector was able to identify failures in this experiment correctly with 99.7% accuracy. All of the errors were false detections, none of the actual failures were missed. The delay between failure and detection varied with average delay of 14.2 samples. Histogram of the delay is given in Figure 3.

DOA estimation performance was analyzed by measuring the angle between true and estimated propagation vectors, and computing the average error as well as the cumulative distribution of error. These metrics were computed for two cases: *combined*, in which all DOA estimates were used and *failure*, where only estimates after sensor failure were used. The average errors in degrees for different methods are given in Table 2. The table includes also

Method	Combined	Failure only	Proper only
LS	14.15	47.89	**2.98**
LS + Proposed	3.40	4.68	2.98
AVG	14.20	47.60	3.15
AVG+Proposed	3.56	4.83	3.15

Table 2. Average errors (angle between true and estimated vectors) in degrees for DOA estimation methods . Errors are computed for three cases: combined (all time delays are used), failure (only time-delays after sensor failure) and proper (only time delays before the failure). LS-solution in proper operation is the reference, marked in bold.

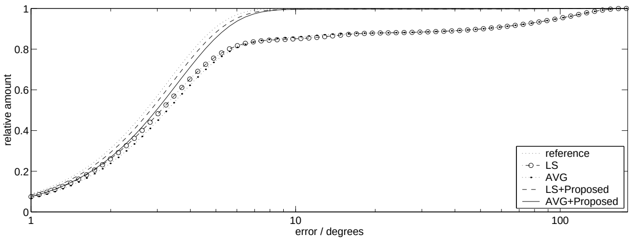

Fig. 1. Cumulative distribution of error (angle between vectors) for DOA estimators with and without proposed failure detection. All estimates (before and after failure) have been used. The proposed failure detection method improves the performance. Degree axis is logarithmic for better visualization.

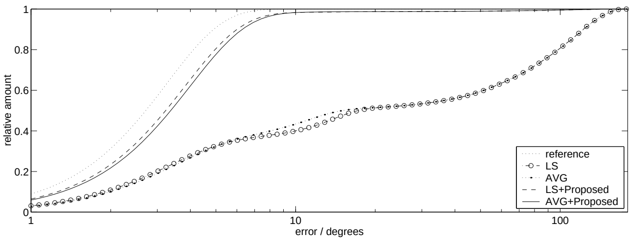

Fig. 2. Cumulative distribution of error for DOA estimators, with and without proposed failure detection. Only DOA estimates after the sensor failure have been used. Performance improvement with the proposed failure detection is clearly visible. Degree axis is logarithmic for better visualization.

average errors in proper operation for comparison. Cumulative distributions of error are given in Fig. 1 for the combined case and in Fig. 2 for the failure case.

Results indicate, that the proposed failure detection method can increase the performance of DOA estimation when a sensor failure occurs. If detection is not used, none of the estimators can tolerate failures. When the detection of a failed sensor is combined with the estimators, the performance is not significantly worse than in proper operation. The differences are caused by the delay of failure detection and also the fact that with fewer sensors available, the errors from quantization are larger. The computational load of the detection is minimal compared to the actual task of time delay estimation. Also, the proposed method can also detect multiple sensor failures, when they do not occur simultaneously.

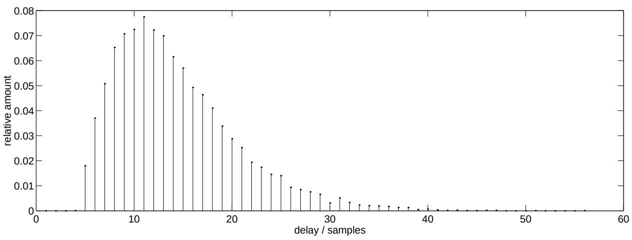

Fig. 3. Histogram for delay (in samples) between failure and detection. Detection buffer length $B = 9$ and threshold $D_{fail} = 5$.

6. CONCLUSIONS

In this paper, a new method was proposed to detect and compensate for the failure of one sensor in an array performing time delay based direction of arrival estimation. The detection was based on confidence factors derived from the planar wave assumption. The performance of the method was demonstrated with simulations. Combining the method with typical DOA estimators significantly increased the performance of DOA estimation in case of a failure. The proposed method enables a sensor system to continue its operation even if one of the sensors has failed and indicates that a failure has occurred.

7. REFERENCES

[1] A. Hero (ed.) et al., "Highlights of statistical signal and array processing," *IEEE Signal Processing Magazine*, vol. 15, no. 5, pp. 21–64, 1998.

[2] S. Haykin and J. Justice, *Array signal processing*, Academic Press, 1985.

[3] M. Brandstein and D. Ward, Eds., *Microphone Arrays*, Springer-Verlag, 2001.

[4] J. C. Chen, Y. Kung, and R.E. Hudson, "Source localization and beamforming," *IEEE Signal Processing Magazine*, vol. 19, no. 2, pp. 30–39, 2002.

[5] J. Yli-Hietanen, K. Koppinen, and J. Astola, "Time-delay selection for robust angle of arrival estimation," in *Proceedings of the IASTED International Conference on Signal and Image Processing*, 1999, pp. 81–83.

[6] "Special issue on time delay estimation," *IEEE Transactions on Acoustics, Speech and Signal Processing*, vol. 29, no. 3, 1981.

[7] F. Viola and W. F. Walker, "Comparison of time delay estimators in medical ultrasound," in *IEEE Ultrasonics Symposium*, 2001, pp. 1485–1488.

[8] J. Yli-Hietanen, K. Kalliojärvi, and J. Astola, "Low-complexity angle of arrival estimation of wideband signals using small arrays," in *Proceedings of the 8th IEEE Signal Processing Workshop on Statistical Signal and Array Signal Processing*, 1996, pp. 109–112.

[9] R. Blumrich and J. Altmann, "Medium range localisation of aircraft via triangulation," *Applied Acoustics*, vol. 61, no. 1, pp. 65–82, 2000.

[10] K. Varma, T. Ikuma, and A. A. Beex, "Robust TDE-based DOA-estimation for compact audio arrays," in *Proceedings of the Second IEEE Sensor Array and Multichannel Signal Processing Workshop (SAM 2002)*, 2002, pp. 214–218.

[11] D. E. Dudgeon and R. M. Merserau, *Multidimensional digital signal processing*, Prentice-Hall, 1984.

[12] J. Yli-Hietanen, K. Kalliojärvi, and J. Astola, "Robust time-delay based angle of arrival estimation," in *Proceedings of the 1996 IEEE Nordic Signal Processing Symposium (NORSIG 96)*, 1996, pp. 219–222.

[13] T. Pirinen, P. Pertilä, and A. Visa, "Toward intelligent sensors - reliability for time delay based direction of arrival estimates," in *Proceedings of the 2003 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP'03)*, 2003.

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