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Data Fusion Functions: Applications to Sensor Networks

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Abstract: A median-based sensor fusion function has been proposed which satisfies local Lipschitz condition and is fault tolerant in presence of outliers. Some of the existing fusion functions have also been merged to produce a hybrid fusion function which satisfies local Lipschitz condition and retains the better properties of each component function. Equivalence has been established between two existing fusion functions under certain conditions. *Copyright © 2009 IFSA.*

Keywords: Fault tolerance, Sensor fusion, Hybrid fusion functions

1. Introduction

Wireless Sensor Networks have established their utility in a very large number of civil and military applications. The main advantage of this technology is the increasing availability of cheaper sensor nodes with higher data processing capabilities and better scalability with perhaps tens of thousands of sensor nodes deployed in some custom applications. Wireless communication has enabled huge number of sensors to stay connected. This has also opened up a new domain for data integration techniques to hierarchically pass useful information from cluster nodes to localized sink nodes and finally to a central information processing station. We refer to this data integration as sensor fusion.

Fault-tolerant sensor fusion is a necessity where some of the nodes in a sensor network may turn faulty due to battery exhaustion or physical wear and tear. This requires robust transmission of sensor data to higher levels in the sensor network hierarchy. The sensor estimates may be crisp valued or interval valued (due to their tolerance limits). As a result, the fused estimate may be crisp or interval valued. There are several approaches to sensor fusion. Using Fusion functions is one of the several approaches. In this paper, we consider the case where the sensor output is interval valued and is a bounded and connected subset of real line R. The fused output from a fusion function is also interval.

Given below are definitions for some of the terms used in this paper:
Abstract sensor: It is a sensor that reads a physical parameter and gives out an abstract interval estimate I_s which is bounded and connected subset of real line R.
Correct Sensor: It is an abstract sensor where the interval estimate contains the true value of the measured parameter.
Faulty sensor: It is an abstract sensor where the interval estimate does not contain the true value of the measured parameter.

Let $I_1, I_2, I_3, \ldots, I_n$ be the interval estimates from *n* abstract sensors and let there be *f* faulty sensor among them.

We summarize the some of the known fusion functions below [1]:

M function of Marzullo [2] : $\boldsymbol{M}([I_1, I_2, I_3, \ldots, I_n])$ is defined to be the smallest interval that contains the intersections of *n-f* intervals. It is guaranteed to contain the true value provided the number of faulty sensors is at most *f*.

F function of Schmid and Schossmaier[3] : $\boldsymbol{F}([I_1, I_2, I_3, \ldots, I_n])$ returns a closed interval [*a*, *b*] where *a* is the $(f+1)^{th}$ maximum left end point and *b* is the $(f+1)^{th}$ minimum right end point of the intervals *i.e.* there are exactly *f* left end points to the right of *a* when the left end points are sorted in non decreasing order and similarly there are *f* right end points to the left of *b* when right end points are sorted in non decreasing order.

Ω function of Prasad et al.[4] : The **Ω**(x) function, also called the overlap function, gives the number of intervals overlapping at *x*. Multi Resolution Analysis(MRA) performed on the **Ω** function results in an integration interval with the highest peak and widest spread at a certain resolution.

N function: **N** function improves over the **Ω** function to only generate the interval with the overlap function having the range [*n- f, n*].

Conventional fault models consider correct and faulty sensors and their corresponding interval estimates. Further, tamely faulty and wildly faulty sensors are so defined based on whether or not their interval estimates overlap that of correct sensors, respectively. With this fault model, it is realized that the fused estimate provided by the **F** function is optimal.

The fault model considered for the median-based fusion function **G** proposed in this paper is such that the sensor measurements contain the sensed value corrupted by impulsive noise. With this fault model, median is a better fault tolerant estimate than the mean.

In this paper, we also propose a Hybrid fusion function which integrates the existing fusion functions to provide a single fused interval having the desirable properties of component fusion functions.

2. Median-based Fusion Function

Median filtering approach provides a robust, fault tolerant estimate in signal processing.

Here we provide an example to compare median and mean of a set of values.

Let the crisp values be {10, 9, 11, 12, 10, 8, 24, 26, 30}. The last three values are outliers (extreme values) and are given out by faulty sensors. The mean gives the estimate as 15.55 while the median gives the estimate as 11. Here we observe that the mean gives a poor estimate than the median.

We will study the median based fusion function along with proof of its Lipschitz criterion.

Median-based Fusion Function **G**: **G** function returns the fused estimate as being the output interval whose left bound is the median of all left end points and whose right bound is the median of all the right end points, i.e., the interval is $[Median\ of\ n\ left\ end\ points, Median\ of\ n\ right\ end\ points]$ where n is the number of sensor nodes in the cluster. Here the number of faulty sensors f must satisfy $\mathbf{f < \lceil n/2 \rceil}$. **G** function also satisfies local Lipschitz condition with respect to uniform metric as in [6]. This means that for small changes in input intervals, the change in output interval is also very small, if any. This is illustrated in Fig 1.

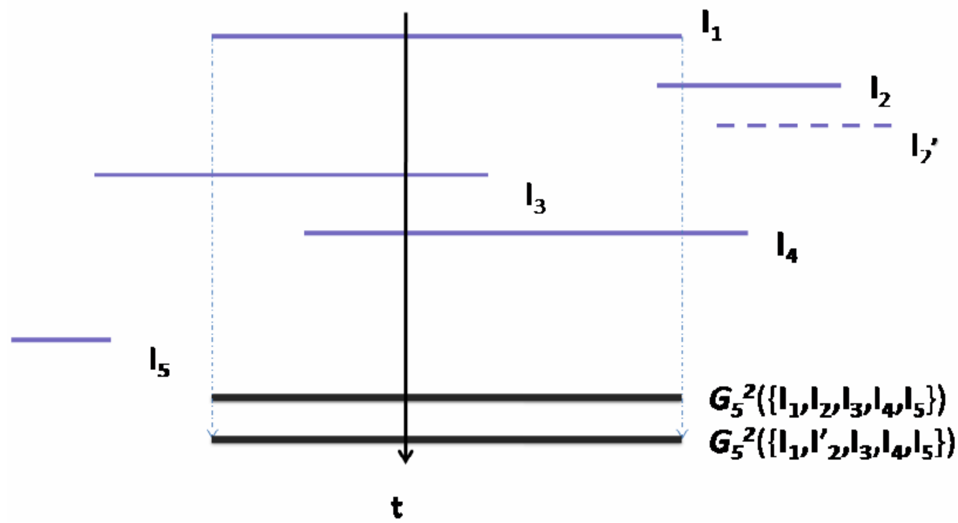

Fig. 1. Example of Median based fusion function **G** with n=5 and f=2. There is no impact of change in I_2 to $I_2^{'}$. Note that t represents the true value of the measured parameter.

The principle behind the median based fusion function can be extended to create a family of related rank order statistic based fusion functions. In general, we can take the i^{th} largest value of all left end points as the left bound and the i^{th} largest value of all right end points as the right bound.

For example, in case of forest fires, we need to have the information about the highest temperature in an area to generate an alarm, in which case the n^{th} largest left and right end points are taken. Similarly, in polar/cold regions, minimum temperature must be emphasized.

The following Lemma gives the Lipschitz condition criterion for the median based fusion function.

Lemma 1: The median based fusion function '**G**' satisfies Lipschitz condition for the uniform metric $\boldsymbol{\mu}$ which means that for any $\boldsymbol{\delta>0}$ and any two sets of interval readings I = { I_1 , I_2 , I_3 ,….., I_n} and $I^{'}$= { $I_1^{'}$, $I_2^{'}$, $I_3^{'}$,….., $I_n^{'}$ } with at most $f < \lceil n/2 \rceil$ of those being faulty,

$\mu(G^f_n(I), G^f_n(I')) < \delta$, provided that $\mu(I_i, I_i^{'}) < \delta$ for $1 \le i \le n$.

Proof: Let **G** = $G^f_n(I)$ and G'= $G^f_n(I')$.

Let $I_i = [x_i, y_i], x_i < y_i$.

$I_i' = [x_i', y_i'], x_i' < y_i'$.

Note that $x_i' = x_i + l_i, y_i' = y_i + r_i$, where $-\delta < l_i, r_i < \delta, 1 \leq i \leq n$.
We consider two cases: *n* is even and *n* is odd.

Case (I): *n* is odd.

$$left(\boldsymbol{G}) = x_j = \left[\frac{n+1}{2}\right]^{th} max.of \{x_1, x_2, x_3, \ldots, x_n\}.$$

$$right(\boldsymbol{G}) = y_j = \left[\frac{n+1}{2}\right]^{th} max.of \{y_1, y_2, y_3, \ldots, y_n\}.$$

$$left(\boldsymbol{G'}) = x_{j'}' = \left[\frac{n+1}{2}\right]^{th} max.of \{x_1', x_2', x_3', \ldots, x_n'\}.$$

$$right(\boldsymbol{G'}) = y_{j'}' = \left[\frac{n+1}{2}\right]^{th} max.of \{y_1', y_2', y_3', \ldots, y_n'\}$$

Here $\mu((x_j, y_j), (x'_{j'}, y'_{j'})) = max\{|x_j - x'_{j'}|, |y_j - y'_{j'}|\}$.

To prove $\mu((x_j, y_j), (x'_{j'}, y'_{j'})) < \boldsymbol{\delta}$, it is enough if we prove $|x_j - x'_{j'}| < \boldsymbol{\delta}, |y_j - y'_{j'}| < \boldsymbol{\delta}$.

Thus we deal with left(**G**) and right(**G**) separately and the proof is similar for both.

We need to prove that $|x_j - x'_{j'}| < \boldsymbol{\delta}$ *if* $\mu(I_i, I_i') < \boldsymbol{\delta}$ *for* $1 \leq i \leq n$.

Consider $x_j' = x_j + l_j$.

Case (1a):

$$x_j' \leq x_{j'}'$$
$$x_j' = x_j + l_j, |l_j| < \delta$$
$$\Rightarrow x_j - \delta \leq x_j' < x_{j'}'$$
$$\Rightarrow x_j - \delta < x_{j'}' \quad (1a)$$

Case (1b):

$$x_j' > x_{j'}'$$

Suppose $\exists$ an $x_k \ni x_k \geq x_j$ and $x_k' \leq x_{j'}'$.

We have $x_j \leq x_k \Rightarrow x_j - \delta \leq x_k - \delta < x_k + l_k \leq x_{j'}'$

$$\Rightarrow\ x_j - \delta < x'_{j\prime} \tag{1b}$$

Therefore from (1a) and (1b) we get

$$x_j - \delta < x'_{j\prime} \tag{1}$$

We need to prove the existence of such an x_k. We adopt the method 'Proof by contradiction'.

Assume no such x_k exists i.e. $\forall\ x_k, x_k \geq x_j \Rightarrow x'_k > x'_{j\prime}$.

$x_k > x_j\ \Rightarrow k$ can take almost $\frac{n-1}{2}$ values.

We arrive at a contradiction.

Therefore $\exists\ an\ x_k$ such that $x_k \geq x_j\ and\ x'_k \leq x'_{j\prime}$

Consider $x'_{j\prime}$

Case (2a):

$$x_{j'} = x'_{j'} - l_{j'} \leq x_j$$

$$\Rightarrow x'_{j\prime} \leq x_j + l_{j'} < x_j + \delta$$

$$\Rightarrow x'_{j'} < x_j + \delta \tag{2a}$$

Case(2b):

$$x_{j\prime} > x_j$$

Suppose $\exists$ an $x_k\ \ni x_k \leq x_j$ and $x'_k \geq x'_{j'}$.

We have $x_k \leq x_j \Rightarrow\ x'_{j'} \leq x_k + l_k < x_k + \delta \leq x_j + \delta$

$$\Rightarrow x'_{j\prime} < x_j + \delta \tag{2b}$$

Therefore from case (2a) and case (2b), we get

$$x'_{j\prime} < x_j + \delta \tag{2}$$

We need to prove the existence of such an x_k.

Assume no such x_k exists i.e. $\forall\ x_k, x_k \leq x_j \Rightarrow x'_k < x'_{j\prime}$.

$x_k \leq x_j\ \Rightarrow k$ can take almost $\frac{n+1}{2}$ values.

But $x'_k \leq x'_{j'} \Rightarrow k$ can take almost $\frac{n-1}{2}$ values.

We arrive at a contradiction which implies that such an x_k exists.

Therefore $\exists\ an\ x_k$ such that $x_k \leq x_j\ and\ x'_k \geq x'_{j'}$.

From (1) and (2), we have

$$\boldsymbol{x_j - \delta \leq x'_{j'} \leq x_j + \delta} \text{ or } |\boldsymbol{x_j - x'_{j'}}| < \delta$$

Case (II): *n* is even

The proof is similar for even number of sensors except that we need to prove for $x_{j1}\ and\ x_{j2}$ separately where $x_j = \frac{(x_{j1}+x_{j2})}{2}$ and $x'_{j'} = \frac{(x'_{j1'}+x'_{j2'})}{2}$

$$x_{j1}\ and\ x_{j2} \text{ are } \left[\frac{n}{2}\right]^{th}\ and\ \left[\frac{n+1}{2}\right]^{th}\ max.of\ \{x_1, x_2, x_3, \ldots, x_n\}.$$

$$x'_{j1'}\ and\ x'_{j2'} \text{ are } \left[\frac{n}{2}\right]^{th}\ and\ \left[\frac{n+1}{2}\right]^{th}\ max.of\ \{x'_1, x'_2, x'_3, \ldots, x'_n\}.$$

Also we know that if $\left|x_{j1} - x'_{j1'}\right| < \delta$ and $\left|x_{j2} - x'_{j2'}\right| < \delta$, then

$$\left|\frac{(x_{j1}+x_{j2})}{2} - \frac{(x'_{j1'}+x'_{j2'})}{2}\right| < \left|\frac{x_{j1}-x'_{j1'}}{2}\right| + \left|\frac{x_{j2}-x'_{j2'}}{2}\right| < \frac{\delta}{2} + \frac{\delta}{2}$$

$$\Rightarrow \left|x_j - x'_{j'}\right| < \delta.$$

Similarly, we can prove that $|y_j - y'_{j'}| < \delta$ Q.E.D

Corollary: Similar argument can be applied to prove tha local Lipschitz condition for the uniform metric for a function that selects the minimum/maximum of the left and right end points. This is useful where we are concernedonly with the minimum or maximum of all the readings, for example, in case of monitoring forest fires or monitoring temperature in polar/cold regions.

3. Hybrid Fusion Functions

In this section we present a method to integrate the existing fusion functions to provide a single output interval. This can be extended to any number of component fusion functions. Moreover, if each of the fusion functions satisfies Lipschitz condition, the hybrid fusion function also satisfies Lipschitz condition. We define the fusion function ***H*** as

$$\boldsymbol{H}\{I_1, I_2, I_3, \ldots, I_n\} = A \cap B \cap C,$$

where

$$A = M\ \{I_1, I_2, I_3, \ldots, I_n\}$$
$$B = F\ \{I_1, I_2, I_3, \ldots, I_n\}$$
$$C = N\ \{I_1, I_2, I_3, \ldots, I_n\}$$

We now prove the Lipschitz condition for the intersection of two fusions functions each satisfying Lipschitz condition independently for a certain metric and extend our result, by induction to the Hybrid fusion function, ***H***, as defined above.

Lemma 2: If f and g are two functions satisfying Local Lipschitz condition for the uniform metric μ over two sets of intervals I, I', then their intersection $f \cap g$ satisfies the local Lipschitz condition.

Proof: Let the vectors I, I' be sensor readings, i.e.,

$$I= \{[x_1,y_1],[x_2,y_2],\dots,[x_n,y_n]\},$$

$$I'= \{[x_1,y_1],[x_2,y_2],\dots,[x_n,y_n]\}.$$

We have $\mu\big(f(I),f(I')\big) < \delta$ and $\mu\big(g(I),g(I')\big) < \delta$ if $\mu\,\big((x_i,y_i),(x_i',y_i')\big) < \delta\ \forall\, i \in \{1,2,\dots,n\}$.

Here $\mu\,\big((x,y),(v,w)\big) = \max\{|v-x|,|w-y|\}$.

To prove $\mu\,\big((x_i,y_i),(x_i',y_i')\big) < \delta$, it is enough if we prove $|x_i - x_i'| < \delta$ and $|y_i - y_i'| < \delta$.

Let f(I),f(I') be $[x_f,y_f]\,and\,[x_f',y_f']$ respectively.

Let g(I), g(I') be $[x_g,y_g]\,and\,[x_g',y_g']$ respectively.

Since f and g satisfy Lipschitz condition,

$$|x_f - x_f'| < \delta \text{ and } |y_f - y_f'| < \delta$$

$$|x_g - x_g'| < \delta \text{ and } |y_g - y_g'| < \delta$$

In order to prove that $f \cap g$ satisfies Lipschitz condition, we need to prove that

$\min(y_f,y_g) - \min(y_f',y_g') < \lambda_2\delta,$

where λ_1,λ_2 are some positive constants.

Consider (3)

$$\max(x_f,x_g) = \frac{1}{2}[x_f + x_g + |x_f + x_g|]$$

Similarly,

$$\max(x_f',x_g') = \frac{1}{2}[x_f' + x_g' + |x_f' + x_g'|]$$

Equation (3) implies

$$\frac{1}{2}\Big|x_f - x_f' + x_g - x_g' + |x_f - x_g| + |x_f' - x_g'|\Big| < \frac{1}{2}(\delta + \delta + |x_f - x_f' + x_g - x_g'|) < \frac{1}{2}(4\delta) = 2\delta$$

Note: Here we have used the ordering property that $|a| - |b| < |a - b|$

Similarly we can prove (4) using

$$min(a, b) = \frac{a + b - |a - b|}{2}$$

Therefore $f \cap g$ satisfies Lipschitz condition if *f* and g satisfy Lipschitz condition individually for the uniform metric.

Corollary: By induction, it can be inferred that if $f_1, f_2, \ldots, f_M$ are fusion functions each satisfying Lipschitz condition, then $f_1 \cap f_2 \cap f_3 \cap \ldots \cap f_M$ also satisfies Lipschitz condition for any finite *M*.

4. M function and F function: Condition for Equivalence

In this section, we compare M function and F function and establish an equivalence relation between the two, subject to certain conditions. It is established that M function does not satisfy Lipschitz condition but F function does. The following lemma provides the condition under which M function satisfies Lipschitz condition.

Lemma 3: M function is equivalent to F function provided

$$\{maximum\ of\ all\ left\ end\ points\} \leq \{minimum\ of\ all\ right\ end\ points\}.$$

In other words, each intersection of any $n - f$ intervals is non-empty.

Proof: Let $\{x_1, x_2, x_3, \ldots, x_n\}$ represent the set containing all left end points sorted in non-decreasing order and $\{y_1, y_2, y_3, \ldots, y_n\}$ represent the set containing all the right end points sorted in non decreasing order.

Total number of intersections of *n-f* intervals chosen from n intervals is given by C_{n-f}^{n} . Alternatively, by looking at the left end points, we can classify these total numbers of intersections into

Number of intersections having x_n as left bound $= C_{n-f-1}^{n-1}$.

Number of intersections having x_{n-1} as left bound = C_{n-f-1}^{n-2} and so on.

Therefore we have number of intersections having x_{n-k+1} as left bound = C_{n-f-1}^{n-k}.

If x_{n-k+1} turn out to be the minimum among left bounds of all C_{n-f}^{n} intersections, then we have

Solving for k, we get $\boldsymbol{k = f + 1}$.

i.e. union of all C_{n-f}^{n} intersections has its left bound as $(f+1)^{th}$ maximum left bound(i.e. x_{n-f}) which is same as that of left bound of F function.

Similar argument can be applied to show that the right bound of the union of all intersections of n-f intervals is the $(f + 1)^{th}$ right bound (i.e., y_{f+1}) when sorted in non decreasing order. Therefore M function gives the same resultant fused interval as F function i.e., $[x_{n-f}, y_{f+1}]$, given that none of the C^n_{n-f} intersections is empty. This is illustrated in Fig. 2 and Fig. 3.

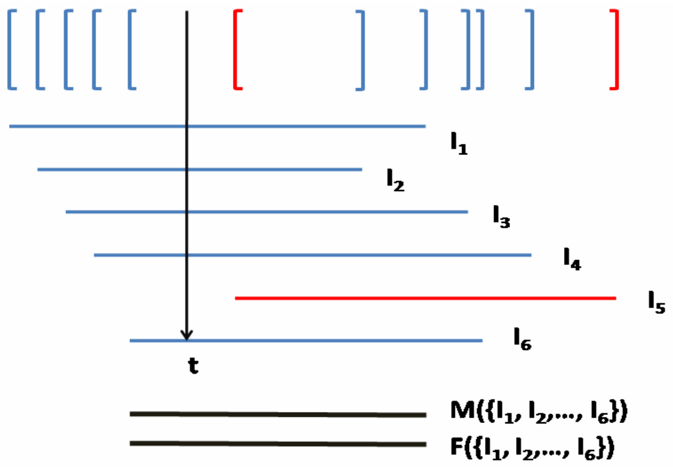

Fig. 2. Scenario where none of the intersections are empty.

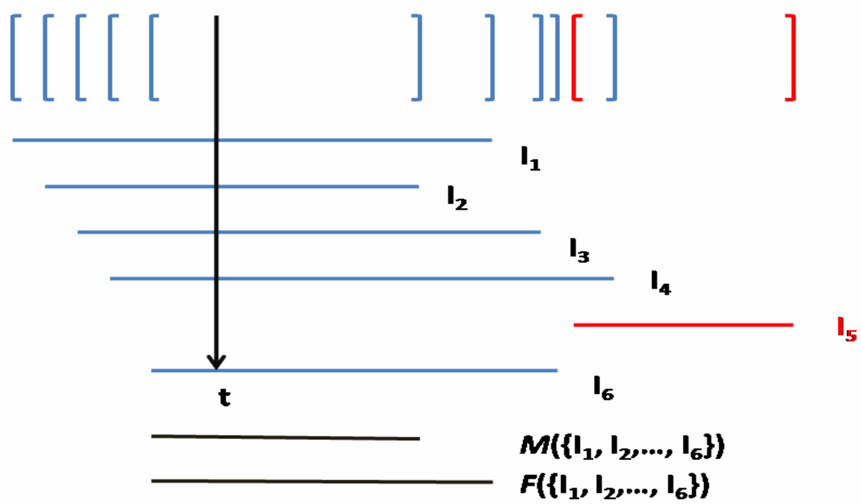

Fig. 3. Scenario where some of the intersections are empty.

Corollary: For the above scenario of having n sensors with f faulty sensors and sensor readings such that

$$\{maximum\ of\ all\ left\ end\ points\} \leq \{minimum\ of\ all\ right\ end\ points\},$$

we can say that all the faulty sensors have their interval outputs either to the left of the true value or to the right of the true value, but not both. Further, the true value(t) lies in $[x_{n-f}, x_n)\ or\ (y_1, y_{f+1}]$ because the region $[x_n, y_1]$ is contained in all intervals including that of faulty sensors.

We can further localize the true value as lying in

- $[x_{n-f}, x_n)$ if all the faulty sensors have their interval outputs to the right of the true value.
- $(y_1, y_{f+1}]$ if all the faulty sensors have their interval outputs to the left of the true value.

5. Uncertain Number of Faulty Sensors: Sensor Fusion

In this section we propose an algorithm for sensor fusion where the number of faulty sensors, f has a discrete probability distribution. The proposed algorithm is as follows:

Given: The abstract readings are $\{ I_1, I_2, I_3, \ldots, I_n \}$ where the minimum and maximum possible values for the number of faulty sensors are f_{min} and f_{max} respectively. Thus the discrete probability distribution of f has the support $\{f_{\min}, f_{min}+1, f_{min}+2, \ldots, f_{max}-1, f_{max}\}$.

The probability mass function is given by
p_i = probability that the number of faulty sensors is i,
$i = f_{\min}, f_{min}+1, f_{min}+2, \ldots, f_{max}-1, f_{max}$.

Algorithm:

1) Consider the fusion function F.
Calculate the fused interval estimates corresponding to each
i, $i = f_{\min}, f_{min}+1, f_{min}+2, \ldots, f_{max}-1, f_{max}$.

2) **Let** the set of fused interval estimates be ,J_i $i = f_{\min}, f_{min}+1, f_{min}+2, \ldots, f_{max}-1, f_{max}$.

3) **Take** the midpoint of each fused interval estimate,
$J_i^{(mid)}$,$i = f_{\min}, f_{min}+1, f_{min}+2, \ldots, f_{max}-1, f_{max}$.

4) **Calculate** the first moment μ of the distribution of the midpoints.

$$\mu = \sum_{i=f_{min}}^{f_{max}} p_i J_i^{(mid)}$$

5) **Calculate** the second moment and then variance, σ^2 of the fused estimates.

$$\sigma^2 = \sum_{i=f_{min}}^{f_{max}} p_i (J_i^{mid})^2 - \mu^2$$

6) **Calculate** the standard deviation σ.

7) **Declare** the estimate as $[\mu - \sigma, \mu + \sigma] or\ [\mu - 2\sigma, \mu + 2\sigma]$, etc depending upon the required fidelity.

6. Conclusions

In this paper we proposed a novel median based sensor fusion function, **F** and hybrid fusion function **H**, for fault tolerant sensor fusion and proved their Lipschitz continuity. This function considers the impulsive noise model different from the **F** function. We have also established the equivalence relation between **M** function and **F** function under certain conditions. In situations where these conditions are satisfied, **M** function can be replaced with **F** function to obtain the same performance with lesser computational overhead. Probability distribution for the number of faulty sensors has also been explored and an algorithm for sensor fusion has also been proposed. Future work would be on applying these fusion functions to real world applications.

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Aims and Scope

Sensors & Transducers Journal (ISSN 1726-5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because it is an open access, peer review international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per annual by International Frequency Association (IFSA). In additional, some special sponsored and conference issues published annually. *Sensors & Transducers Journal* is indexed and abstracted very quickly by Chemical Abstracts, IndexCopernicus Journals Master List, Open J-Gate, Google Scholar, etc.

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