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FIRE LOCATION ESTIMATION USING TEMPERATURE SENSOR ARRAYS

1. ABSTRACT

This paper reconsiders how to estimate the location of a fire in a closed room with an array of temperature sensors. The very important question is: “Where is a fire located ?”. The answer is of interest for research on fire detection and for a deeper understanding of the case of fire for prevention and extinguishing. The answer to this question can be given with two small arrays of temperature sensors. Here, “small” means in the same dimensions like a standard fire detector. The data signal processing for the fire location estimation can be done by a digital signal processor (DSP). It seems to be possible to give a rough fire location estimation with such an array in the same time which is required by a standard fire detector to give a fire alarm.

2. INTRODUCTION

One of the main concerns in fire research is to detect a fire in a short time with a low false alarm rate. It is also of interest *where* a fire is located. For example two scenarios will be given. First an automatic fire extinguishing in a sensible area like a ware house or a computer room. The damage in such an area can be minimized with knowledge of the fire location and a more exact automatic extinguishing can be done. Hence, the cost can be reduced. The second scenario is a fire extinguishing by a fireman in a smoky room. Knowledge of the fire location before entering the room minimizes the extinguishing time. It can also minimize the danger for his life while entering a room with such deadly smoke.

Now we take a look at a fire in an early stage. The hot gases are rising up from the fire place near the floor to the ceiling shown in figure 1 a). Under the ceiling they propagate in a circular shapes as shown in figure 1 b).

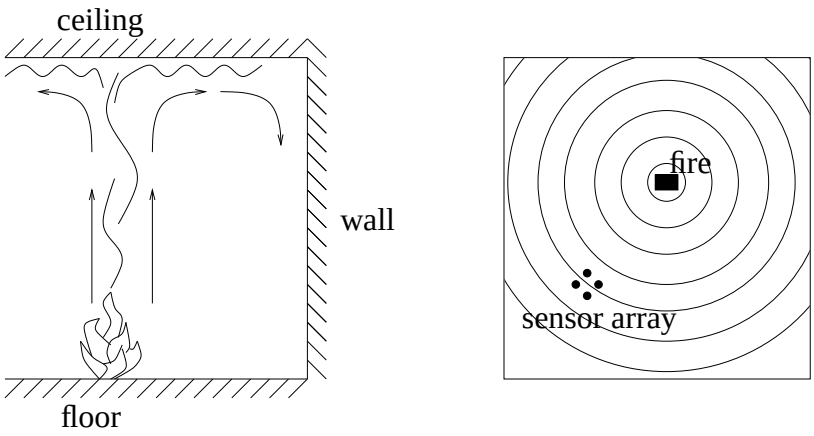

Figure 1: a) fire in a closed room (sideview) b) circular wave shapes (topview)

Due to more or less strong turbulences and interferences caused by the rooms walls the shapes will not be perfectly circular. If we take now an average in time we expect an almost circular shape. This observation is fundamental for the following idea. However, these circular behavior seems to be time limited. When a fire grows up, the hot gases become more turbulent, and the propagation becomes more and more non-circular shapes.

Here, our basic approach. For the following considerations some boundary conditions must be fulfilled:

- The ceiling should be flat with a low heat conductivity.
- The flow current velocity $\vec{v}$ of the hot gases should be nearly constant under the ceiling in the early state of fire.
- The fire is near the floor level
- The walls are of the same temperature.
- The fire is not located directly at a wall.
- Other air currents,e.g. caused by a heating system, should be neglected.

These assumptions are needed to validate the waveform as of almost circular shape. With these assumption the hot gases grow up vertically from the fire and reach the ceiling with the shortest distance. From this point the circular shapes starts under a nearly flat ceiling. In this case the estimation can be reduced from a three dimensional problem into a two dimensional problem.

In the following always an array of four sensors is used. The sensors are arranged in a quadratic way and located at the points (x_n, y_n), $n = 1(1)4$ with a distance $d = 5$cm. The active part of the sensor (diameter 0.13mm) is mounted 8mm under the ceiling. These parameters differs from earlier publications on this topic [3], [4], [7]. Modern ceramical NTC resistors are used in a temperature range from 0° C up to more then 150° C. Thus, a high dynamic of these sensors is required. The used sensors have a low response time around 0.11s in air [8]. Also a low tolerance is required, which is guaranteed here by careful selection.

3. THEORETICAL FUNDAMENTALS

The propagation of the hot gases under the ceiling can be seen as a temperature wavefront $T(x,y,t)$ with (x_0, y_0) as the location of the fire. With a flat ceiling a radius r can be defined as

$$r = (x - x_0)^2 + (y - y_0)^2.$$

Since the wavefront $T(x,y,t)$ is assumed to be of a circular shape it is only a function of the radius and time. Hence, we use the notation $T(r,t)$ instead of $T(x,y,t)$ in the following. For a sensor on a fixed point (x_n, y_n) the temperature function $T(t)|_{r_n}$ is only a function of time. Sampling is required for the data processing. The frequencies in the case of fire are limited up to $\approx$ 10Hz [2], so that we assumed to use a sample frequency of $f_A = 20$Hz . So the temperature samples from b sensors at the location (x_n, y_n) can be seen as

$$T_n(k) = S_n(k) + N_n(k), \quad n = 1(1)b$$

where $S_n(k)$ is interpreted as a deterministic signal caused by the fire and $N_n(k)$ as noise caused by the unavoidable turbulences. If the range r is large between the fire place projection under the ceiling (x_0, y_0) and the location of the sensor array (x_n, y_n), the temperature wave under the ceiling can be seen as a quasi planar wavefront from the perspective of the array with the dimensions $d \times d$ and $d \ll r$.

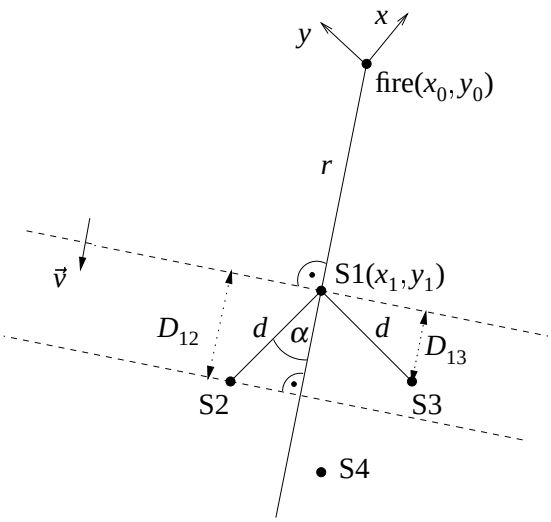

Figure 2: geometrical arrangement of the sensor array

In figure 2 the sensor array with sensors $S_n, n = 1(1)4$ is shown in the distance r from the fire place projection under the ceiling. The wavefront is shown as quasi planar with the velocity $\vec{v}$.

Figure 2 also shows, that with knowledge of the geometric order of the sensors in the array and the assumption of a quasi planar wavefront with the velocity $\vec{v}$ first reaches the sensor S1, then S3, then S2 and last S4. With this model a time delay can be defined between S1 and S2 as D_{12} and also D_{13} as delay between S1 and S3.

With knowledge of this coherence and our signal model the problem of estimation the direction can be reduced using the geometry of the sensor array to a time delay estimation problem

$$T_1(k) = S(k) + N_1(k)$$

$$T_n(k) = \alpha_n S(k - k_{1n}) + N_n(k), \quad n \neq 1$$

with the delays k_{1n}. The deterministic signal $S(k) = S_1(k)$ as a part of $T_1(k)$ is interpreted as a time delayed signal $S(k - k_{1n})$ also in $T_n(k)$, $n \neq 1$.

We have investigated several signal processing algorithms known on time delay estimation, e.g. the PATH-algorithm, the SCC-algorithm, the SCOT-algorithm, the WIENER PROCESSOR, the ROTH PROCESSOR, the ML-algorithm and the Adaptive Time Delay Estimation method. For details see [9]. In the following only the SCC-algorithm (Simple

Cross Correlation) is explained to understand the principles of time delay estimation. The cross correlation between the first and the n sensor output is

$$R_{1n}(\kappa) = E\{T_1(k)T_n(k+\kappa)\}, \quad n = 2(1)4.$$

By the assumption of uncorrelated noise $N_n(k)$ in the signal model, it can be written as

$$R_{1n}(\kappa) = E\{S(k)S(k-k_{1n}+\kappa)\}, \quad n = 2(1)4.$$

The maximum of $R_{1n}(\kappa)$ occurs for $\kappa = k_{1n}$, since the argument takes for arbitrary $s(k)$ a positive value. For estimation of k_{1n} now only the cross correlation has to be estimated and its maximum has to be found. Normally the estimation $\hat{R}_{1n}(\kappa,k)$ is given by averaging the temperature sample vectors from $T_1(k)$ and $T_n(k)$.

$$\hat{R}_{1n}(\kappa,k) = \frac{1}{L}\sum_{l=m}^{L+m-a} T_1(l)Tn(l+\kappa), \quad n = 2(1)4, \quad k = \frac{m}{M},$$

$$m = 0(M)K-L, \quad \kappa = -\kappa_{max}(1)\kappa_{max}.$$

In the following the hat indicates an estimation. The in-stationarity of the signals is taken into account by the time dependence $k = \frac{m}{M}$ of $\hat{R}_{1n}(\kappa,k)$. The measured signals are composed to non overlapping blocks with the length L. The estimation is only calculated each Mth time. κ_{max} should be not too large to minimize required calculation power.

After knowing the estimated time delays, we just need the relations between these delays and the parameters r, α and $\vec{v}$. We have assumed that the fire is far away from the array, so that $r \gg d$ and we can see them as quasi planar wavefronts. So the velocity vector can be seen as

$$|\vec{v}|\frac{k_{12}}{f_a} = d\cos\alpha$$

$$|\vec{v}|\frac{k_{13}}{f_a} = d\sin\alpha.$$

So the parameters α and $\vec{v}$ can be written as

$$\alpha = \arctan(\frac{k_{13}}{k_{12}})$$

$$|\vec{v}| = f_a\frac{d\cos\alpha}{k_{12}}.$$

Actually the fourth sensor S_4 is unused, so it can be used to estimate another pair of delay times. These delay times can be also used to calculate an estimated angle and velocity

to verify and also to improve the first calculation. For the location estimation a second estimated angle information is required. In our case we place another angle estimation unit in the same observation room. With these two estimated angles α_1 and α_2 a location of the fire can be calculated.

4. FIRE EXPERIMENTS

All fire experiments were carried out in the fire detection laboratory of the GERHARD-MERCATOR-University Duisburg. The fire room of the laboratory has a ground size of 10.5m $\times$ 9m and the variable ceiling (it can be varied from 2.87m up to 6.57m) was fixed at 3.40m. Some first experiments [3],[4] with spirit fire were carried out to test out the generic work of the location estimation algorithm. After an optimizing process for some boundary conditions on the algorithm parameters seven kinds of test fire were done. The test fires are listed in table 1 by name, number and burning material.

TF1	Open wood fire (beechwood)
TF2	Smoldering (pyrolysis) wood fire (beechwood)
TF3	Glowing smoldering fire (cotton)
TF4	Flaming plastic fire (polyurethane)
TF5	Flaming liquid fire (n-Heptane)
TF6	flaming liquid fire (metylated spirit)
TF7	Flaming liquid fire (dekalene)

Table 1: Test fires by name and material

To verify the different algorithms with test fires a fixed angle between the sensor arrays and the fire location was used. For the fire experiments two sensor arrays are mounted under the ceiling. The physical parameters are $\alpha_1 = 45°$, $\alpha_2 = 45°$, $r_1 = 3m$ and $r_2 = 3m$, the fire was always located at $(x_0, y_0) = (0, 0)$.

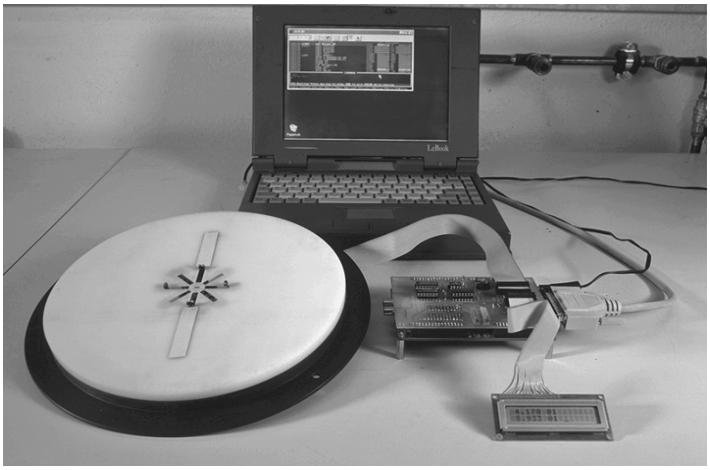

Figure 3: Sensor array, signal processor and PC

The measurement system, shown in figure 3, uses a disc with a diameter of 23cm. In its center the temperature array containing four sensors is placed. The figure also shows the used Digital Signal Processor (DSP) board, liquid crystal display and data acquisition computer. For a detector solution with DSP we minimized the required calculation power and used memory. The sample rate was shifted down to $f_A = 20$ Hz. The observation window length L was minimized to 40 samples. All shown angle estimations are calculated with the *SCC*-algorithm. The reason for this selection was the first portation of this algorithm into a DSP for an automatic angle estimator. In [9] is shown that the error between the *SCC*-algorithm and other, more calculation intensive algorithms is small enough for a first solution.

To verify the results from the DSP solution an additional computer-based simulation with the algorithm under test has been done. The estimation algorithms has been tested with all of the listed kinds of test fires. But exemplified by three of these fires should be shown that the estimation works. Only the first 80 seconds of a test fire are shown in the following figures, because the goal of the estimation was to give a first fire location estimation at the time of fire alarm. For example the detection time for a TF6 and an European standard temperature detectors of class A1 is around 60 seconds. The detector must give an alarm after the room temperature increases by 29° Celsius. The alarm here is given by a temperature of 50° Celsius depending on a room temperature of 21° Celsius before the fire starts.

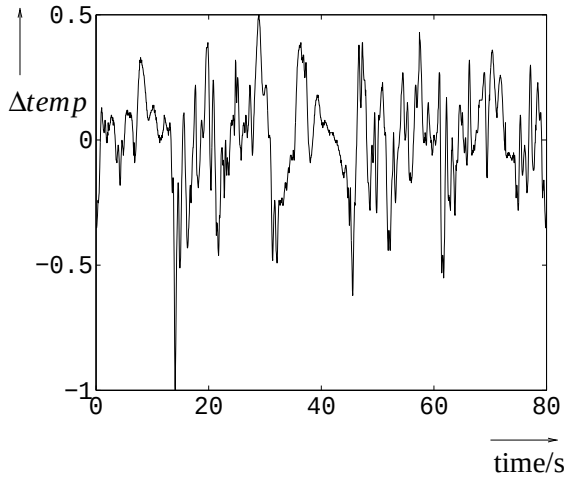

Figure 4: TF2 temperature data

Figure 4 shows the temperature curve from a sensor which is typical for smoldering fire type TF2. This signal and the following signals shown in figure 6 and figure 8 showed no temperature dc offset, so they can be interpreted as shown after a high pass filtering. These signals includes the lightning of the fire in their first ten seconds.

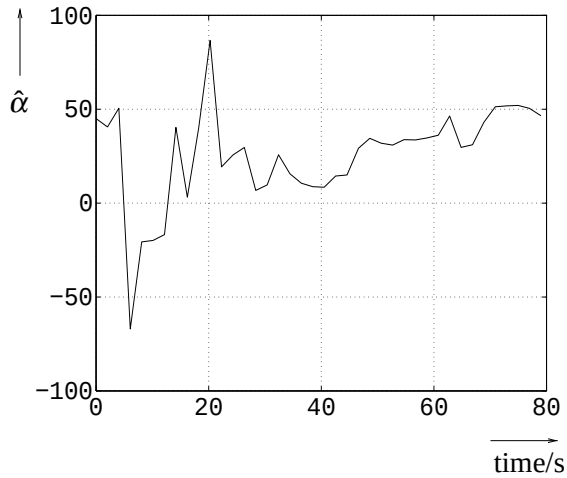

Figure 5: Estimated angle $\hat{\alpha}$ for a TF2

The figures 5, 7 and 9, shows the estimated angle value $\hat{\alpha}$ for the first 80 seconds of a fire. There is an angle $\hat{\alpha}$ value for every two seconds depending on a 40 sample correlation window length L and a f_A =20 Hz sample rate. The estimated angle $\hat{\alpha}$, shown in figure 5 varies $\Delta\alpha = -12 \ldots +8$ degrees around true real value after 60 seconds.

Figure 6 shows the temperature curve from a sensor which is typically for a flaming fire

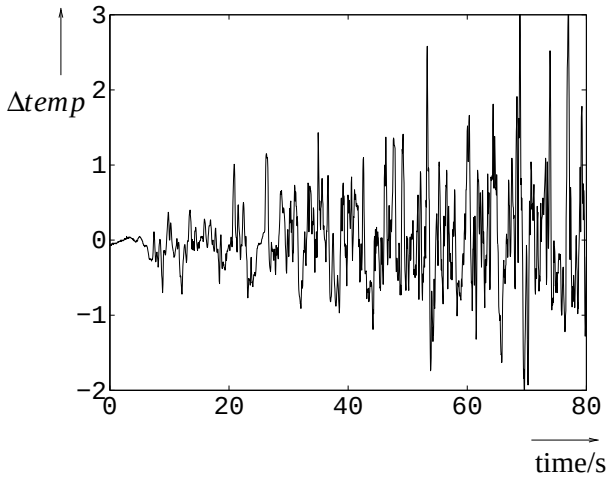

Figure 6: TF4 temperature data

type TF4. The typical increasing temperature values over the time indicate that the time is limited for estimating the fire place. This is caused by increasing the turbulences of the hot gases under the ceiling from the increasing fire.

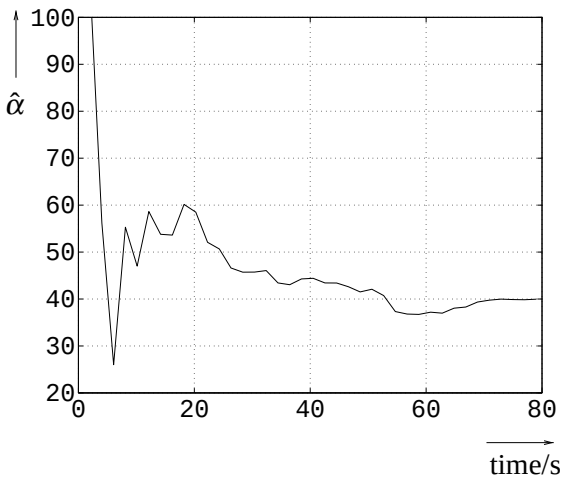

Figure 7: Estimated angle $\hat{\alpha}$ for a TF4

The estimated angle $\hat{\alpha}$, shown in figure 7 varies $\Delta\alpha = -10 \ldots +3$ degrees around the real value after 40 seconds.

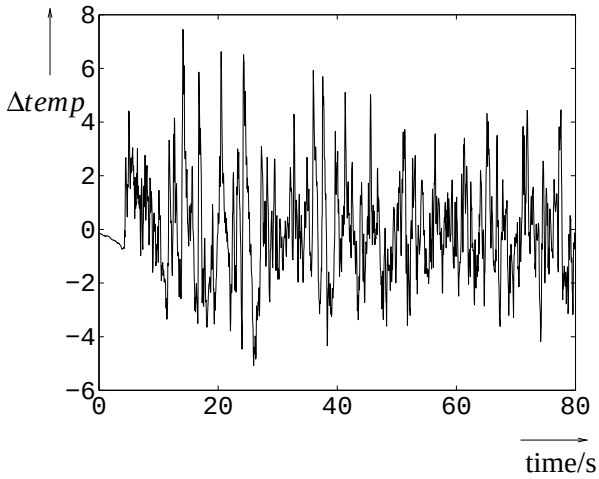

Figure 8: TF6 temperature data

Figure 8 shows the temperature curve from a sensor which is typically for a flaming liquid fire type TF6.

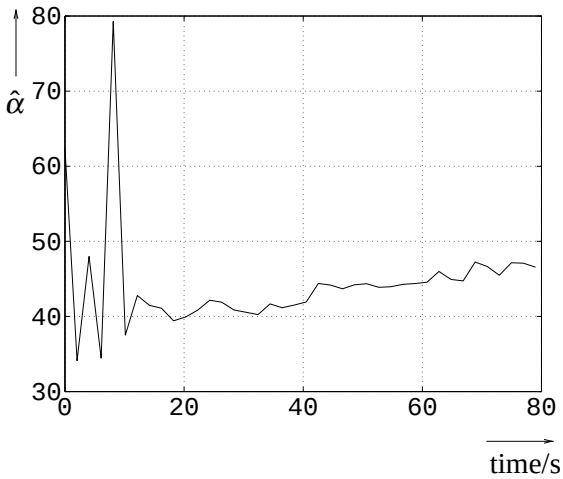

Figure 9: Estimated angle $\hat{\alpha}$ for a TF6

The estimated angle $\hat{\alpha}$, shown in figure 9 varies $\Delta\alpha = -8 \ldots +4$ degrees around the real value after 20 seconds and $\Delta\alpha = -5 \ldots +3$ degrees after 40 seconds.

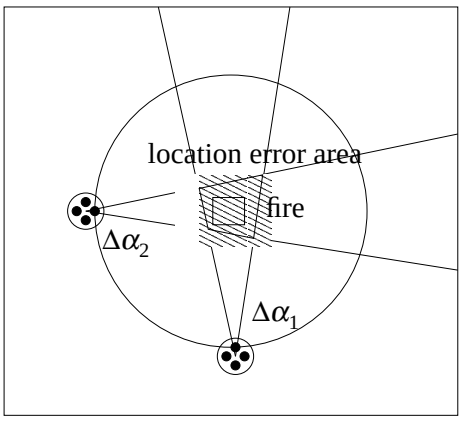

Figure 10: The location estimated error area

Figure 10 shows the error area of the location estimation in the fire laboratory under our test conditions. For example the TF6 is a flaming liquid fire in a quadratic basin with 43.5cm $\times$ 43.5cm and the error area from the estimation is in the same dimensions.

5. CONCLUSION

A method to locate a fire using two temperature arrays was proposed. A first DSP solution was shown and it's results were verifyed by fire experiments. It was shown that it is possible to give a first fire location estimation in the same time as needed for detecting the fire with a class A1 detector. Unknown is the time for an useful location estimation of smoldering fires of type TF2 and TF3. For the future it is planed to port some other promising time delay estimation algorithms to the DSP solution for a higher accuracy. It is also planned to test some other sensor types e.g. pyroelectric sensors for their useful work in such a detector type.

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