An Application of IEEE 802.15.4™ for Locating and Monitoring Thermal Hotspot using High Directivity Mobile Sensor

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***Abstract*— The rationale behind the project is to obtain a low cost alternative to thermal imaging cameras, for industries that require higher level of automation or may not afford them. A mobile device is built which is equipped with two temperature sensors that detect and locate local high temperature spot on a machine and alerts concerned personnel about the nature of problem. The process is completed in two stages, where in the first stage average temperature of the machine is obtained, in the second stage precise location of the hot-spot is found. Upon finding temperatures beyond set limits, the device alerts the controller with information regarding location of hot-spot and temperature. The proposed device finds application in environments that use temperature sensitive machines and require strict monitoring for fault conditions. In this project, we have investigated the advantages and effectiveness of IEEE 802.15.4 standard, for such a purpose. As it is evident, timely response and accurate control impose strict requirements of highly predictable and real-time behavior of overall system. Tests on timing performance of device revealed that it can locate a hotspot in less than a minute on a machine (while performing scan in angular area of 90° (horizontal) * 45° (vertical)). Moreover, the possibility of avoiding detailed scan due to high FOV sensor greatly improves performance in practical conditions.**

***Index Terms*—IEEE standards, ZigBee, thermal sensors**

I. Introduction

THE world is constantly moving toward industrial automation. The aim behind the project is to be a part of the revolution and explore yet another dimension of machine interaction. Most industrial sites use machines that have performance dependent of their temperature. However, mainly two broad methods are used for temperature monitoring: first of which is to use temperature acquisition systems permanently embedded at sensitive sites and second is to have personnel equipped with thermal cameras periodically checking for faults. First method, despite being effective and intuitive, is redundant and costly for sites where temperature spikes are rare. Second method, on the other hand, has limitations in form of possible human errors and latency.

The researchers thus resolved to find a solution involving cost effectiveness, efficiency and quick-predictable response. The method thus designed is to use non-contact temperature sensors (as opposed to those used in first method discussed above) and one-dimensional sensors (as opposed to thermal cameras, which are two-dimensional). The advantages achieved through such a balance of both methods are as below:

- The region scanned by permanently embedded sensors is often too small. Non-contact thermometers can be used to acquire information regarding temperature of larger portion of machine.
- Thermal camera despite being capable of observing large portion of machine, need a processor to analyze data or carry out complex calculations in order to predict possibility of future errors. While the sensors used here provides direct temperature information about the objects under the area being scanned.
- Cost effectiveness is achieved over both methods discussed above, with lesser trade-offs.
- Machines can be expected to be more predictable and can work for longer periods as compared to humans. Thus a robot, patrolling a certain area can be expected to work faster than a human allotted with same task.

The temperature sensors, used here, are discussed in section II. While in section III, IEEE 802.15.4 standard is discussed in brief which is followed by section IV, in which the developed prototype is discussed.

II. Temperature Sensors

After exploring various sensors available in the market, MLX90614, [1] manufactured by Melexis was considered the most suitable for task. These sensors consist of a thermopile (MLX81101) to sense temperature and a signal conditioning system (MLX90302) to process the output of sensor before it is available to the device controlling it. As a result temperatures are available with resolution of 0.01° C and accuracy of 0.5° C at room temperature. These sensors come in some variants, each with a different FOV (Field Of View). Higher FOV means that sensor will have more objects within its vision, and it will thus provide temperature as an average of individual temperatures of objects in its FOV. Such a high FOV can be used to have a broader idea of an object's temperature when sensor is placed right in front of the object. On the other hand, low FOV sensors are very sharp and can be considered to read the temperature of a "point" toward which they are pointed. For the project, two sensors chosen are of 35° and 10° FOV respectively.

It should be noted that it is possible to use just the low FOV sensor, since it alone can provide all the data necessary for computer to recognize and locate any fault. However, the advantage available due to an additional sensor (one with high FOV) is in the time taken to acknowledge the presence of a fault. At working level, if high FOV sensor indicates that (average) temperature of a particular machine is well inside safe range, there won't be any need to scan whole structure using low FOV sensor. If instead, temperature is found close to or above specified limit, the low FOV sensor would be used to scan whole structure and locate hotspot. It is thus evident that, with two sensors, the time taken to scan whole structure may not be spent unless there is a possibility of a fault.

The sensors also provide another valuable feature at user's disposal. The output of sensors, which is temperature of object in front of it, can be acquired in two formats. First one is to read internal RAM of sensor by means of 2-wire SMBus communication [10] and second one is to configure the sensor to provide PWM output. Thus depending upon the nature of processor preferred by designer, analog or digital outputs can be obtained. Although the authors have chosen to use digital output, the PWM output may also be used as a trigger to other circuits, whenever required.

III. IEEE 802.15.4

The detailed study of IEEE 802.15.4 has been done, but only overview is presented here.

The protocol structure of 802.15.4 contains PHY and MAC layers only [4] [9]. The upper layers are user defined.

A. PHY LAYER

IEEE 802.15.4 defines three operational frequency bands: 2.4 GHz, 915 MHz and 868 MHz. Other tasks of which that the PHY layer takes care are:

- *Activation and deactivation of the radio transceiver*:
  The radio transceiver can operate in three different modes: receiving, transmitting, or sleeping. The radio is turned ON or OFF upon request of the MAC sub-layer to PHY layer.
- *Receiver Energy Detection (ED):*
  It estimates the received signal power within the bandwidth of an IEEE 802.15.4 pre-decided channel. Typical usage is for determining whether the channel is busy or idle in the Clear Channel Assessment (CCA) procedure or by the Channel Selection Algorithm of the Network Layer.
- *Link Quality Indication (LQI):*
  It is related to measurement characterizing the strength and quality of a received signal on a link.
- *Clear Channel Assessment (CCA):*
  This operation is responsible for reporting the medium activity state: busy or idle.
  The Assessment can be performed in the following different operational modes:
  - Energy Detection mode: If the received energy is higher than a predefined threshold, referred to as ED threshold, the CCA reports that the medium is busy.
  - Carrier Sense mode: Only if CCA detects a signal having the modulation and the spreading specifications of IEEE 802.15.4 and which may be higher or lower than the threshold above mentioned, the medium is reported busy.
  - Carrier Sense with Energy Detection mode: A combination of the aforementioned methods.
- *Channel Frequency Selection:*
  27 different wireless channels are defined in IEEE 802.15.4 and a network can be operated within a given channel set. The PHY layer tunes its transceiver into a specific channel upon a request from a higher layer.

The standard specifies the following PHYs, in [10].:

- An 868/915 MHz direct sequence spread spectrum (DSSS) PHY employing binary phase-shift keying (BPSK) modulation.
- An 868/915 MHz DSSS PHY employing offset quadrature phase-shift keying (O-QPSK) modulation.
- An 868/915 MHz parallel sequence spread spectrum (PSSS) PHY employing BPSK and amplitude shift keying (ASK) modulation.
- A 2450 MHz DSSS PHY employing O-QPSK modulation.

B. MAC LAYER

As defined in IEEE 802.15.4, the MAC layer provides an interface between the physical layer and the higher layer protocols [5]. It deals with all access to the physical radio channel and is also responsible for the following tasks:

- Generation of network beacons if the device is a coordinator
- Synchronizing to the beacons
- Providing support to PAN association and disassociation
- Supporting device security

- Employing the CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) mechanism for channel access
- Handling and maintenance of the GTS mechanism
- Providing a reliable connection between two peer MAC entities

The MAC protocol also supports two operational modes that can be selected by the coordinator: Beaconless and Non Beaconless mode.

C. Zigbee

ZigBee is a specification for a suite of high level communication protocols using small and low-power digital radios based on the IEEE 802.15.4 standard. ZigBee devices can be interfaced to the computer or other end points [3]. We need a ZigBee modem in order to connect to user understandable digital interface, such as the processors or computer itself. Zigbee Modems can be connected to the USB port of the computer, and can be mounted on a COM port (a standard serial port).

The devices can communicate with each other using the ZigBee module in a Mesh, Tree or Star topology. As a result, ZigBee modems can be used to communicate with many ZigBee devices and we can choose with which device we want to communicate. There are two ZigBee modules, series 1 and series 2. ZigBee Series 2 offers a new feature called mesh networking [8]. Mesh networking allows our devices to communicate with modules that are out of range by talking to devices that are in between.

D. Rationale to choose ZigBee as preferred communication platform for emergency response

One of the main design goals of our system is to have a low power and cost effective Wireless Network. Currently bluetooth offers short personal area coverage however it does not offer the Mesh or Tree networking of ZigBee. Bluetooth is also an IEEE 802.15 WPAN standard and also uses the 2.4-GHz unlicensed frequency band. Like ZigBee Bluetooth also uses small form factors and low power. ZigBee can activate (go from sleep to active mode) in 15 milliseconds or less, the latency can be very low and device can be responsive – particularly compared to Bluetooth wake-up delays of around 3 milliseconds. Thus, ZigBee can be allowed to sleep for most of the time, resulting into a long battery life. Some more technical differences between Bluetooth and ZigBee can be found in [2].

IEEE IEEE 802.11 standard specification provides MAC and PHY layers which can also be used for effective indoor communication over several hundred meters. Here we compare IEEE 802.11, 802.15.4 wireless standards with an emphasis on the physical layer in [2].

Interfacing of 802.15.4 to 802.11 devices can be found in [2].

E. Other wireless standards

The standards given below are version of 802.11 and 802.15 which apply to low-latency networks only, a comphrensive study is found in [3].

IV. DEVELOPED PROTOTYPE

A black line, with white bordering region is chosen for the purpose. Upon turning on the robot immediately seeks the line which it has to follow and begins the scanning task upon encountering a specific strip-pattern on the line. But, this demanded paths to be spread all over the region where the device is supposed to be used. Hence, a device has been proposed which is built to work with reference of two stationary references. The task is performed using two ultrasonic sensors which help to maintain a predefined distance from the two static references which are, in our case, two walls of the room. The first sensor will aid the device for forward and reverse movements. The modules are 35 cm apart from each other in our case, so the sensor will help device to stop at every 35 cm, with respect to the wall which is in front of the device, for scanning while the second sensor will control robot's deviations from the path in left and right directions with respect to another stationary reference, which is the wall in the left side of robot. The deviation control plays pivotal role as the robot is required to be driven parallel to the modules to be scanned.

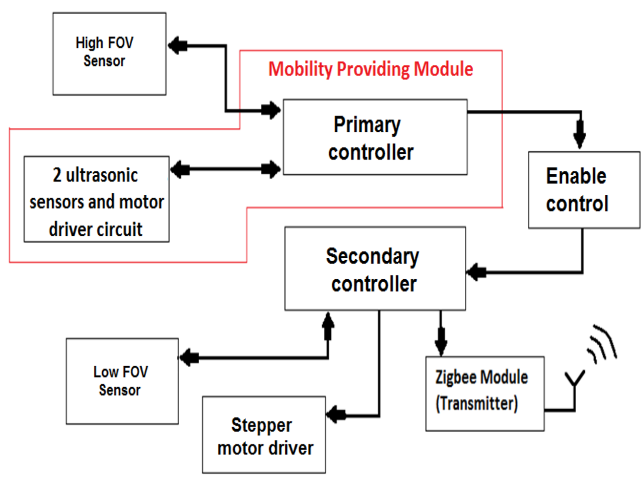

Figure 1. Block Diagram

The ultrasonic sensors used here have range of 4 meters to detect an object [7]. The timing diagram of HC-SR04 is shown. To start measurement, Trig of SR04 must receive a pulse of high (5V) for at least 10us, this will initiate the sensor will transmit out 8 cycle of ultrasonic burst at 40kHz and wait for the reflected ultrasonic burst. When the sensor detected ultrasonic from receiver, it will set the Echo pin to high (5V) and delay for a period (width) which proportion to distance. To obtain the distance, measure the width (T_{on}) of Echo pin [7].

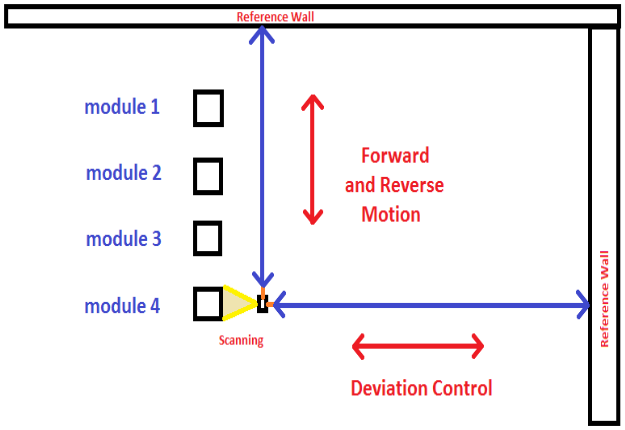

Figure 2. Working Diagram

Time = Width of Echo pulse, in uS (micro second)

- Distance in centimeters = Time / 58
- Distance in inches = Time / 148
- Or the speed of sound can also be utilized, which is 340m/s

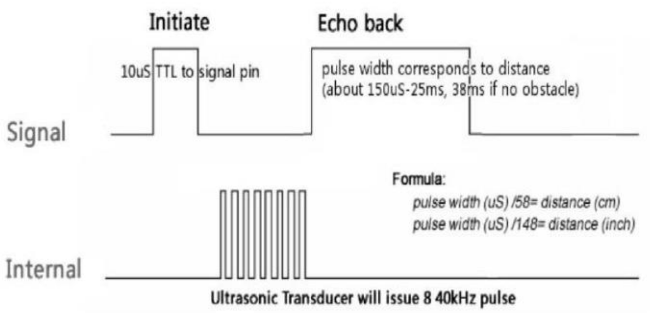

Figure 3. Working of Ultrasonic Sensor

Upon stopping for a scanning site, robot immediately reads the temperature from its high FOV sensor. This sensor, as mentioned above, provides with an average temperature of machine. Using previously stored data related to safe working condition of machine, the robot decides whether to scan further or not. If there is a possibility of elevated temperatures, the robot stops and proceeds to detailed scanning.

The first step in detailed scan is to enable a secondary controller, which commands low FOV sensor, stepper motors and communication module. Although it is not necessary to keep secondary controller disabled during other work, it can be expected to save precious battery power, which is a key factor for performance indicators of mobile devices. Two stepper motors allow controller to point low FOV sensor in a region covered by 90° horizontal and 45° vertical. Although these values are presently assumed for a field of view resembling human vision, they can be configured easily to suit the needs of particular environment or even differently for individual machines. Using such a structure, controller can examine any point of interest on the machine. If any point is found to have temperature level beyond acceptable values, a central computer is alerted immediately via ZigBee communication module. If no faults are discovered, the robot proceeds to scan other machines.

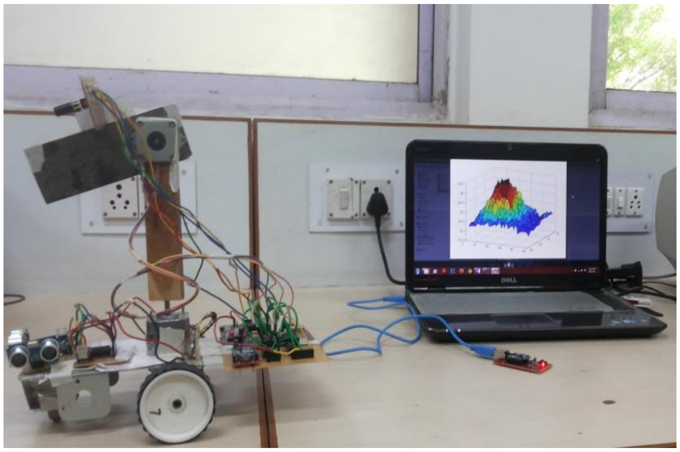

Figure 4. Developed Prototype along with plot of received data

V. Performance Analysis

A. Sensor Performance

When a hotspot was detected during test scans, all the temperature values were sent to the computer instead of only those concentrated around hotspot. A plot generated on MATLAB using these values better represents the device performance. The colors toward red on the spectrum represent higher temperatures and the colors toward blue represent lower temperatures. Moreover, figure 6 shows 3 Dimensional view of the same scan.

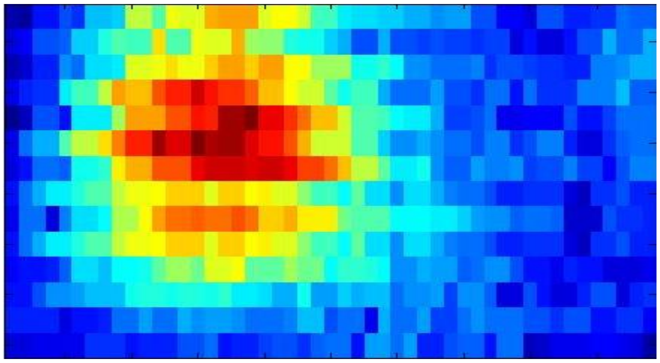

Figure 5. MATLAB generated 2 D plot of thermal scan

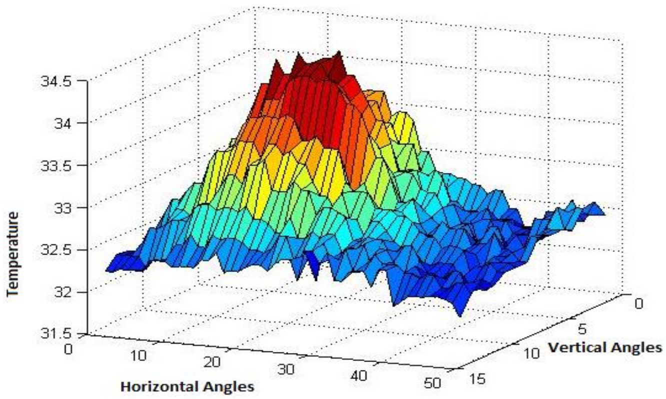

Figure 6. MATLAB generated 3 D plot

B. Timing Performance

It was observed that the device required on average 60 seconds to perform detailed scan and 5 seconds to transmit data on Zigbee and to measure value using high FOV sensor, which is the condition for detailed scan.

Say, *D* is the distance between two machines located side-by-side, *n* is the total number of such machines and *v* is the velocity of the robot. Now total time to scan each machine once gives the time period of complete scanning process.
Period = Time to travel + time to scan

$$\text{Period} = \frac{2nD}{v} + (5 + 60f) * n \quad (1)$$

i.e. if a machine can heat up from normal state to dangerous state within time less than *Period* it may not be detected by said device.

C. Performance Improvement

The performance improvement through use of such two-step process instead of performing detailed scan on all devices can be shown as:
Say, *f* is the fraction of machines that pass the temperature threshold for detailed scan.
Total time in two-step process per machine = 5 + 60f second
Total time in one-step process per machine = 60 second

$$\text{Performance improvement} = \frac{60}{5+60f} \quad (2)$$

i.e. if 10% of machines in a given factory require detailed scan, achieved performance improvement is 545.45%.

VI. CONCLUSION

In overall assessment said device appears to provide a close substitute to thermal cameras in situation requiring regular monitoring of machine temperatures. Further possible enhancements may include a possible camera (visual camera, non-thermal) along with the device to capture “live” image of machine. Such an extension may allow visual inspection of possible damage before any maintenance crew reaches actual location. In addition, with a possibility of transmitting whole set of captured temperatures along with visual image, it is possible to overlay temperature data on the image using graphic processing at receiver end. Such overlaid display can aid in better understanding of the cause behind elevated temperature as it provides temperatures of all relevant-irrelevant parts of machine. Another possible enhancement would be to capture temperature data of same machine from multiple viewpoints. Since such a process generates some redundant data about the same phenomenon, it can be thus used to improve further the accuracy of location of hotspot. Apart from mentioned enhancements, authors also resolve to improve upon the limitation in navigation aspect for the device. So far only two methods have been explored viz. line following and ultrasonic distance measuring sensor based navigation. Possible solutions may include use of INS (Inertial Navigation System) based processor to allow higher flexibility in targeted path or ultrasonic distance sensors aided by magnetic compass for accurate navigation or a combination of both.

APPENDIX

Pseudo code

D= initial distance measured by ultrasonic sensors from primary reference for moving forward
CD= current distance from the same reference
T= distance between two adjacent modules to be scanned
S= initial distance from secondary reference (to control deviation)
CS= current distance from secondary deviation

/*If the mobile device is put in front of first module to be scanned then D= f(T). Thus, the device has to stop for scanning at every T distance i.e. D=T, 2T, 3T and so on.*/

/* We have 5 modules here to be scanned*/

```
Int i=0;
If(Flag==1)    //indicating move forward
{
While (i< 5)
   {
   If( CS == S)
      {  Deflect device to the left or right accordingly}
   If(C= = D – i*T)
   Increment i;
   Stop for primary scanning
   If( temperature > threshold temperature)
      {2 axis scan of front of the module with secondary scanner
      If (temperature at any point > critical value)
         {Transmit data over zigbee}
      }
Else
Move forward
}
}
```

/*When the device will complete scanning the last module, the Flag will be set to zero.*/

```
If(Flag == 0)
{
/*The same logic mentioned above will work. But, the counter will decrement. And the logic to provide current to the motor will be reversed. */
}
```

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