Development of Occupant Detection System Using Far-Infrared Ray (FIR) Camera

Tatsuya IZUMI*, Hiroaki SAITO, Takeshi HAGIHARA, Kenichi HATANAKA and Takanori SAWAI

In recent years, to reduce the risk of airbag-related injuries, smart airbag systems, which deploy airbags depending upon occupant position and crash information, are increasingly being developed. For occupant detection, various methods using weight/pressure sensors, ultrasonic sensors or image sensors, are proposed, but it is difficult to sense precisely a passenger's size and position. FIR cameras, which offer thermographic images, are useful for detection of the human body. The authors have developed low cost FIR cameras using polycrystalline sintered zinc sulfide (ZnS) lenses, which are based on Sumitomo Electric's material technology, and also developed an algorithm for detecting automobile occupants. In this paper, the authors present an overview of the newly developed FIR camera and the occupant detection algorithm.

Keywords: FIR Camera, Lens design, sintered zinc sulfide ZnS, automobile, occupant detection algorithm

1. Introduction

To improve automobile safety, the use of Supplemental Restraint System (SRS) airbags which protect passengers during a collision, has become more common in recent years. Airbags are being mounted onto not only the driver's seat and front seats, but also the rear seats as well as to the side of the seats. On the other hand, fatal accidents caused by airbags have also been reported with its increasing use. In the United States, the use of "smart" airbag systems is becoming mandatory, and the further improvement for automobile safety is to be expected [(1)]. This "smart" airbag system deploys the airbag with optimal control, which is determined by detecting the collision conditions and the seating position of the passenger. Consequently, a sensor that is able to detect the occupant position and physique in high precision is necessary.

Passenger detection methods using various sensors, such as weight/pressure sensors, ultrasonic sensors or visible-ray cameras have been proposed. At Sumitomo Electric Industries Ltd., the authors focused their attention on a camera that would visualize heat (Far-infrared rays) emitted from the passenger. They developed a Far-Infrared Ray (FIR) camera using Sumitomo Electric's material technology on polycrystalline sintered zinc sulfide (ZnS) lens, along with an algorithm to detect automobile occupants. This paper presents a technological overview (lens design, evaluation technology, and signal processing technology) of the newly developed camera and also reports on the details of the passenger detection algorithm and the experimental evaluation results of the detection system.

2. Automobile Occupant Detection System Using Far-Infrared Ray (FIR) Camera

Weight/pressure sensors and ultrasonic sensors are commonly known for its use in passenger detection sensors. Although these sensors are able to detect the presence of an object, they cannot distinguish between passengers and objects, and also have difficulty detecting the precise physical size and position of the passenger. Other passenger detection methods are also used, with visible-ray cameras and Near-Infrared Ray (NIR) cameras through image processing; however, from the principle that these cameras detect and visualize reflected light from the environmental light, they are easily affected by disturbance. In contrast, Far-Infrared Ray cameras visualize an object's "heat," and therefore, there are high expectations for its use in applications to detect humans, such as passengers and pedestrians. **Photo 1** shows a passenger inside a vehicle taken with the FIR camera, and **Photo 2** shows a FIR image of a pedestrian walking in front of the automobile. FIR cameras are often said to have the following advantages/disadvantages:

Photo 1. Image of FIR camera (a passenger inside a vehicle)

Photo 2. Image of FIR camera (pedestrians walking in front of the automobile)

1. Advantages
• Easily detects passenger presence and distinguishes between passengers and luggage, since passenger skin has comparatively higher temperature in the camera image.
• Unlike visible-ray cameras and NIR cameras, FIR cameras are not affected so much by disturbance such as sunlight and headlights.
2. Disadvantages
• Difficult to attain contrast between passengers and background objects if the temperature inside the automobile increases.
• Lens and detectors (focal plane array) are both expensive.

Figure 1 displays the structure of the newly developed automobile occupant detection system. In order to obtain high passenger detection performance, after filming the occupant in the passenger seat with the FIR camera, the image is processed using the passenger's skin temperature information to detect the presence, physique, and position of the passenger and then display the information onto the monitor. Also, to compensate for the above stated disadvantages of the FIR camera, the authors at Sumitomo Electric have developed a bright lens that captures contrast between the passenger and background and an image processing technology that is able to measure the absolute temperature of the passenger, as well as a passenger detection algorithm based on skin temperature. These are described in detail below.

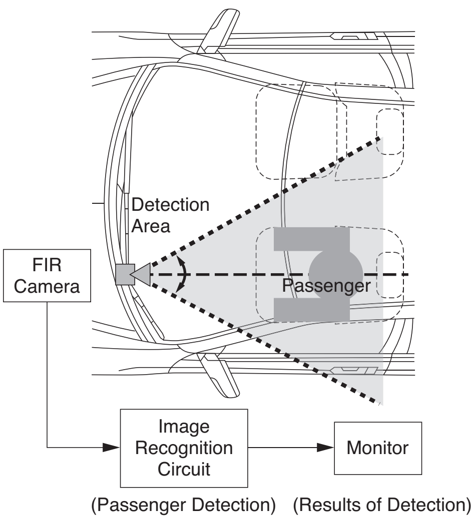


Fig. 1. Newly developed automobile occupant detection system using FIR camera

2-1 Lens Design/Evaluation for Automobile Occupant Detection System

The cost of Sumitomo Electric's original optical material based on ZnS is comparatively lower than Germanium or Chalcogenide glass and other FIR optical materials. Additionally, the production cost is significantly reduced because powder metallurgy is used for the molding process. However, there are also some known drawbacks due to its material property compared to other materials. For example, the wavelength dependence of the refractive index is larger and the transmittance is considerably lower because of the material's inner absorption (see **Table 1**). At Sumitomo Electric, the optical performance weaknesses due to the material property are compensated using their original optical design technology. As a result, the optical performance, in terms of the modulation transfer function (MTF) and temperature resolution, has shown satisfactory results. Also, an original design database is being compiled since optical design using sintered ZnS as the lens material is uncommon, so that a design environment which is able to accommodate various optical specifications may be constructed.

Table 1. Characteristics comparison of infrared optical materials (representative values)

	Sintered ZnS	Germanium	Chalcogenide glass
Refractive index at 10 μm	2.2	4.0	2.5 – 2.6
Abbe number 8 - 12 μm	22.7	942	100 – 120
Thermal coefficient of refractive index (dn/dT) $[10^{-6}]$	39	400	55 – 58
Thermal expansion coefficient $[10^{-6}]$	6.65	6.1	16 – 17
Density $[g/cm^3]$	4.08	5.33	4.4 – 4.8
Absorption coefficient at 10 μm $[cm^{-1}]$	0.20	0.020	0.007 – 0.015

(1) High Contrast Wide-Angle Lens Design

For the newly developed occupant detection system, the camera is installed within the vehicle. The camera target is the passenger sitting in a comparatively close range, and therefore, compared to applications targeting pedestrians such as a night vision system, a wide-angle lens is required. The specifications for the camera prototype are shown in **Table 2**. The distance to the camera target (0.5

Table 2. Specifications of the camera prototype

Item	Specifications
F-Number	F/0.94
Field-of-View	H52 [degrees] × V40 [degrees]
Resolution	320 × 240 [pixel]
Pixel Pitch	25 [μm]
Wavelength	8 - 12 [μm]
Intensity Resolution	8 bit (256 level) gray scale
Camera Size	H45 × W55 × D95 [mm]
Image Output Format	NTSC

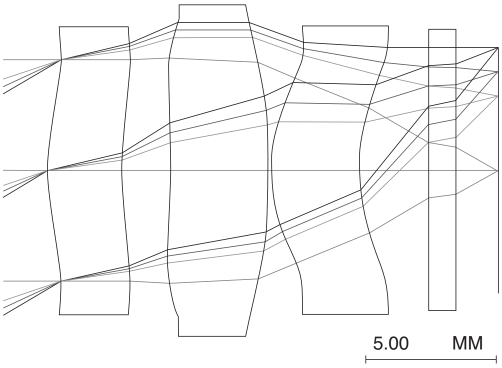


Fig. 2. Ray diagram for the designed lens

~ 2 m), pixel number of focal plane array (320 x 240), and resolution required for the passenger detection algorithm were considered in making the horizontal field-of-view 52 degrees. Also, to obtain sufficient contrast (temperature resolution) for passenger detection, the f-number was designed to be as small as possible but still be able to secure optical performance, such as MTF and distortion.

The ray diagram for the designed lens is shown in **Fig. 2**. The optical system is composed of 3 lenses: lens 1, lens 2, and lens 3, with each lens surface having an aspheric surface. To create a wide-angle using only few lens, normally the curvature of the lens must be made larger, but this posed a problem in which the spherical aberration, coma aberration, and distortion would increase. This was solved by creating an aspheric surface for the center and periphery of each lens surface so that the positive and negative ends of the refractive power would be inverted. In this way, the behavior of the axial light ray and off-axis rays could be controlled precisely, so that the spherical aberration and coma aberration could be corrected. The chromatic aberration caused by the dispersion of the refractive index, was reduced by implementing diffractive optical element (DOE). The MTF property and aberration diagram for the designed lens are shown in **Fig. 3**.

(2) Lens Performance Assessment

OPT-IR (Optikos Corporation, LWIR OpTest Lens MTF System) was used for the MTF property evaluation. The field angle of the test lens and focal point adjustment are automated for this device, and thus the measuring speed is accelerated and also the measurement repeatability is increased. The MTF evaluation results for the experimental wide-angle lens are shown in **Fig. 4**. The MTF at the Nyquist frequency (20 lp/mm) is 0.47 for a field angle of 0 degrees, 0.36 for a 20 degree field angle, 0.26 for a 26 degree field angle, and 0.42 for a 32 degree field angle. As you can see, the results show good MTF for the axial and off-axis field angle.

The temperature resolution for the lens performance was evaluated using noise equivalent temperature difference (NETD) relative to the master lens, assuming the NETD to be 100 mK when measuring with a combination of Sumitomo Electric's master lens (F/1.01) and test camera. A measurement system similar to the one shown in **Fig. 5** was constructed and a differential blackbody source was used to create a test chart. Images taken with a camera using the test lens was then analyzed to calculate the NETD. As shown in **Table 3**, the experimental wide-angle lens has a temperature resolution performance almost exactly as expected in the design.

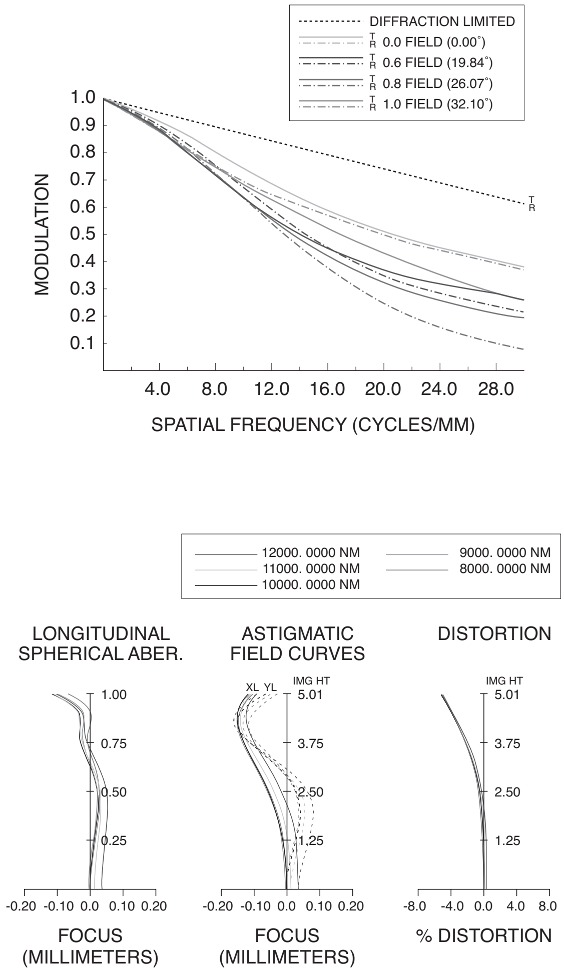


Fig. 3. MTF property and aberration diagram for the designed lens

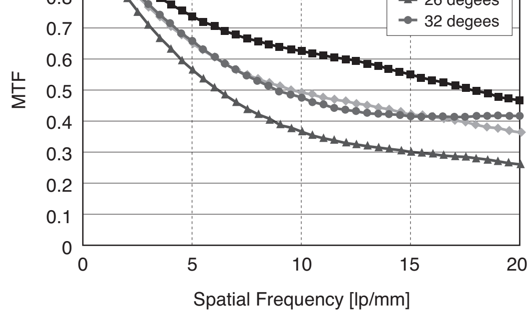


Fig. 4. MTF evaluation results for the developed wide-angle lens

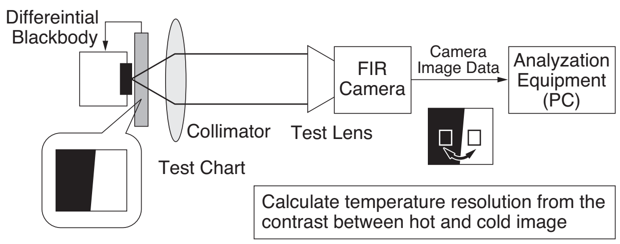


Fig. 5. Test system of temperature resolution performance

Table 3. Evaluation results of temperature resolution

Item	F-Number	Relative NETD (Designed value)	Relative NETD (Measured value)
Master Lens	1.01	100	100
Developed Lens	0.94	86.6	83.3

2-2 Camera Signal Processing Technology Capable of Absolute Temperature Measurement

Compared to the outside environment of the vehicle, there are less heat emitting sources within the vehicle and so, temperature information is extremely useful for detecting passengers. For example, if the passenger's skin temperature (approximately 30+ degrees) can be measured accurately based on camera images, the passenger can be easily distinguished from the background using the passenger detection algorithm, and therefore, an improvement in the precision of passenger detection can be expected. Thermographs are commercially available to measure the temperature of an object precisely, but these are very expensive and not suited for automotive use. The authors have developed a technology to precisely measure the absolute temperature of an object using a low-cost camera. The details are reported below.

The absolute temperature measurement system was constructed so that the temperature sensor output (temperature data) would be inputted to the camera from a temperature sensor capable of measuring absolute temperature, placed within the field of view of the FIR camera (See **Fig. 6**). The luminance value of the object with a temperature sensor installed and the absolute temperature obtained from the temperature sensor are matched to each other, then gain A and offset B is calculated (see **Fig. 7**). In this system, the absolute value T is calculated based on the luminance value of the measurement target object (T = Ax + B).

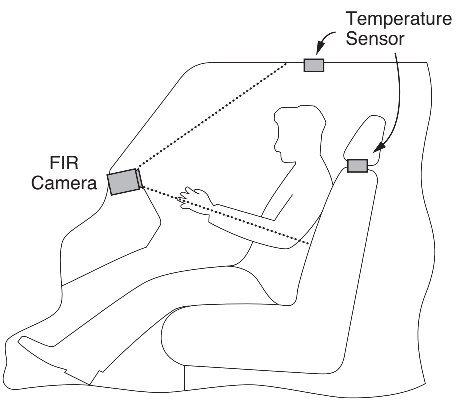


Fig. 6. Absolute temperature measurement system

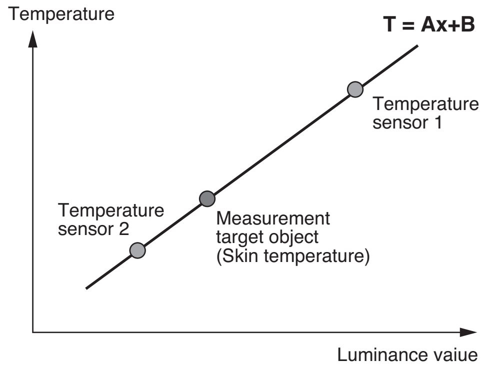


Fig. 7. Calculation method of absolute temperature

Photo 3 shows the exterior of the test camera, and **Fig. 8** shows the block diagram of the signal processing circuit. In the signal processing circuit, the output of the focal plane array goes through analog to digital (A/D) conversion then undergoes a few calibration processes such as fixed pattern noise correction and bad pixel correction. Following this step, the output data goes through image correction processes such as gain control and offset control, and then is outputted to a PC or monitor after being converted into image data (analog or digital signal). The absolute temperature calculation is done during the calibration process and the absolute temperature range that was set beforehand is cut out during the image correction process.

Photo 3. Exterior of developed FIR Camera

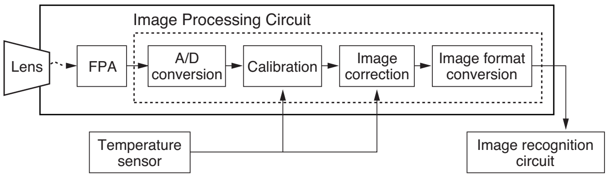


Fig. 8. Block diagram of the image processing circuit

Photo 4. Absolute temperature measurement using FIR camera

Using the simple method to measure absolute temperature from above and a temperature sensor, the calculated passenger skin temperature from the camera image came out to be within ± 1 °C accuracy (within a range of +20 ~ 40 °C) when compared to the actual temperature (measured with a contact thermometer). An example of a camera image is shown in **Photo 4**.

2-3 Automobile Occupant Detection Algorithm

This algorithm determines the presence and position of the passenger based on the absolute temperature measurement technology described in section 2-2, which detects the regions in the FIR camera image with a temperature equivalent to skin temperature and recognizes it as the head region. However, simply using the temperature information alone could not overcome the phenomena listed below, thus allowing for a possibility of an error in the detection of the passenger presence and position.

- If the temperature inside the vehicle is too high, for example right after the engine start-up during the summer, the contrast between the background and skin would be insufficient and there is a possibility that the passenger will assimilate into the background
- When the passenger's "hand" is near the head region, the head and hand are detected as a single item, and an error in the size and position of the passenger may occur
- FIR is reflected by glass, and so a false image of the passenger appears from the window glass on the passenger's side

As a countermeasure for the above problems, a technology that would precisely detect only the passenger's head region using the edge of the image was developed. Since a high precision passenger detection system was successfully created, the details are reported below.

Figure 9 shows the flowchart for the detection algorithm. First, a skin temperature range is set based on the constant correlation between the vehicle interior temperature and the passenger's skin temperature, and only the regions in the FIR image that correspond to the skin temperature are detected. The skin temperature corresponding regions may contain background objects, and therefore an image without any passengers (background image) is prepared beforehand. Both the background image and current image are detected for edges, and the differences of the edges are calculated to determine and erase the objects that belong to the background. Next, in order to differentiate the "head region" from the "hand," the skin temperature corresponding regions are divided into smaller regions. Then, the edge detector is used to distinguish the head region by recombining the divisions that satisfy the head region size conditions, calculated based on positional relationship of the camera and passenger. In order to identify and delete the false image reflected from the window, the edges that belong to the window are selected beforehand from the background image edges. Then the difference between the background image edges and current image edges are calculated to determine the missing window edges. Specifically, the skin temperature corresponding regions on the window are either 1) a passenger leaning toward the window (overlapping with the window) or 2) a false image reflected by the glass. The image is deleted only when the window edge is found to be missing and is determined to be a false image. Lastly, the build and position of the passenger is determined based on the detected head region position and outputted to the monitor.

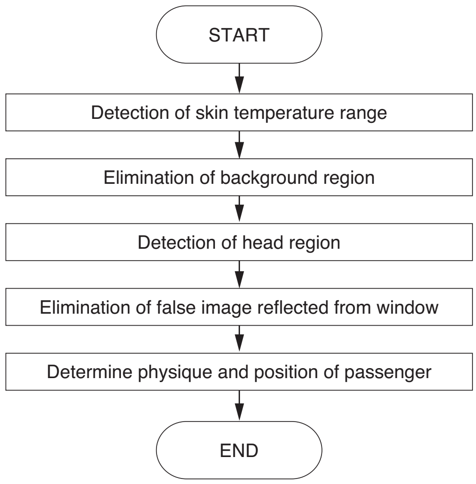


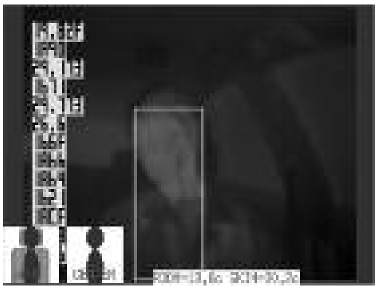
Fig. 9. Flowchart of the passenger detection algorithm

2-4 Verification Experiment

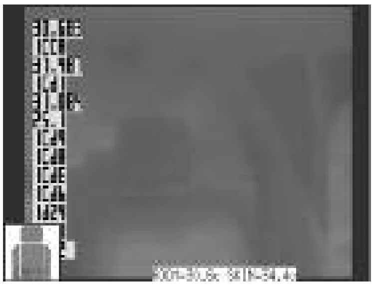
A verification experiment was conducted to examine the detection performance of the FIR camera for the identification the presence, physique, and position of the passenger using the newly developed algorithm. The algorithm was applied to the FIR camera images taken with a variable in-vehicle temperature between +20 ~ 40 °C, controlled using an air conditioning. By categorizing the images using the classification chart shown in **Table 4**, the results confirmed a satisfactory detection performance. The algorithm process results are shown in **Fig. 5**.

Table 4. Classification for body type and position of passenger

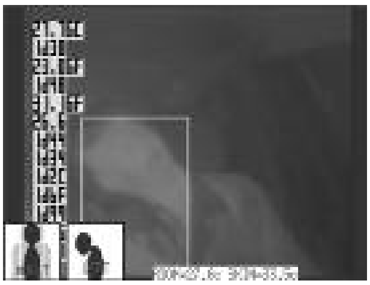
No.	Presence	Physique	Position
1	Empty	–	–
2	Exist	Adult	Center
3	Exist	Adult	Left
4	Exist	Adult	Right
5	Exist	Adult	Not Determined
6	Exist	Child	Center
7	Exist	Child	Left
8	Exist	Child	Right
9	Exist	Child	Not Determined



(a) Passenger exists / Adult / Center



(b) Passenger doesn't exist



(c) Passenger exists / Adult / Left

Photo 5. Process results of occupant detection algorithm

3. Conclusion

The authors developed a FIR camera using Sumitomo Electric's original optical material, sintered ZnS lens, and evaluated the passenger detection performance of the automobile occupant detection system. By using a high contrast wide-angle lens and a low-cost and structurally simple signal processing circuit technology to measure the skin temperature of the passenger, an excellent detection performance in terms of detecting the passenger's presence, physique and position were observed. The FIR camera was also verified to be a valid sensor for in-vehicle occupant detection.

In the future, the authors plan to 1) develop a smaller and lower costing camera (acquire performance of a lower resolution sensor) and 2) investigate other applications for the FIR camera.

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Contributors (The lead author is indicated by an asterisk (*)).

T. IZUMI*

- Automotive Technology R&D Laboratories
  He is engaged in the research and development of devices for in-vehicle safety systems.

H. SAITO

- Automotive Technology R&D Laboratories

T. HAGIHARA

- Assistant Manager, Automotive Technology R&D Laboratories

K. HATANAKA

- Manager, Automotive Technology R&D Laboratories

T. SAWAI

- General Manager, Automotive Technology R&D Laboratories