Thermal infrared reference sources fabricated from low-cost components and materials

Harald Hovland, Torbjørn Skauli

Harald Hovland, Torbjørn Skauli, "Thermal infrared reference sources fabricated from low-cost components and materials," Proc. SPIE 10625, Infrared Imaging Systems: Design, Analysis, Modeling, and Testing XXIX, 1062507 (26 April 2018); doi: 10.1117/12.2306330

Event: SPIE Defense + Security, 2018, Orlando, Florida, United States

Thermal infrared reference sources fabricated from low-cost components and materials

Harald Hovland, Torbjørn Skauli
Norwegian defence research establishment (FFI), P O Box 25, N-2027 Kjeller, NORWAY

ABSTRACT

Mass markets, including mobile phones and automotive sensors, drive rapid developments of imaging technologies toward high performance, low cost sensors, even for the thermal infrared. Good infrared calibration blackbody sources have remained relatively costly, however. Here we demonstrate how to make low-cost reference sources, making quantitative infrared radiometry more accessible to a wider community. Our approach uses ordinary construction materials combined with low cost microcontrollers, digital temperature sensors and foil heater elements from mass-market 3D printers. Blackbodies are constructed from a foil heater of some chosen size and shape, attached to the back of a similarly shaped aluminum plate coated with commercial black paint, which normally exhibits high emissivity. The emissivity can be readily checked by using a thermal imager to view the reflection of a hot object. A digital temperature sensor is attached to the back of the plate. Thermal isolation of the backside minimizes temperature gradients through the plate, ensuring correct readings of the front temperature. The isolation also serves to minimize convection gradients and keeps power consumption low, which is useful for battery powered operation in the field. We demonstrate surface blackbodies (200×200 mm^2) with surface homogeneities as low as 0.1°C at 100°C. Homogeneous heating and low thermal mass provides for fast settling time and setup/pack-down time. The approach is scalable to larger sizes by tiling, enabling portable and foldable square-meter-size or larger devices.

Keywords: Blackbody, Infrared, Low cost, Calibration, Microcontroller, Digital temperature sensor, 3D-printer , Thermography.

1. INTRODUCTION

Low cost infrared imaging has found its way into a large range of consumer products, notably in the mobile phone and automotive market. Using techniques for mass production in optics and electronics, high quality imagers with high pixel counts are becoming available at prices that make them interesting in an increasing range of everyday items.

Despite the high imager quality available, calibration sources remain expensive and essentially unavailable to the wider community of users. At prices easily ranging beyond several tens of thousands of dollars, even university groups may have problems acquiring more than one blackbody of appropriate size. Temperature control is often presented to be in the range of one degree accuracy or better, but this is normally valid only in a very controlled laboratory environment.

For remote sensing, it can often be necessary to have available very large surface blackbodies, given that the point spread function, or the pointing accuracy of the sensor to be examined, is not always as sharp as desired. As the f-number of the optics may change with focus, it is not always a solution to refocus the camera after calibration. Also, if the typical target fills a relatively small part of the field of view (FOV), it may make sense to have available a controlled reference point on a controlled background, hence requiring a relatively large reference source on a very large controlled background. This may represent challenges that go beyond cost, as most blackbodies are relatively inefficient in terms of power consumption.

We will in this paper examine some fundamental issues regarding black body fabrication, and demonstrate how the emergence of the Maker movement, with the ensuing wide availability of low cost components an materials, combined with consideration of basic thermal physics, enables anyone, anywhere, to build low cost blackbody sources with sufficient quality for many applications.

Infrared Imaging Systems: Design, Analysis, Modeling, and Testing XXIX, edited by Gerald C. Holst, Keith A. Krapels,
Proc. of SPIE Vol. 10625, 1062507 · © 2018 SPIE · CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2306330

2. PARTS AND CONSTRUCTION METHODS

In this chapter we review some of the components and techniques that enable construction of low-cost reference sources.

2.1 Temperature measurement

Classic analog temperature sensors such as thermocouples and thermistors are still widely used. Here we make use of digital sensors to avoid the need for analog front end electronics. New digital temperature sensors, such as Analog Devices ADT7420, provide sensor temperature accuracy of ±0.25°C from -20°C to +105°C, in a 4 mm × 4 mm × 0.75 mm package[2]. A sensor from Maxim Integrated[3], the DS18B20, provides a measurement range from -55°C to +125°C, with ±0.5°C accuracy from -10°C to +85°C. Such sensors can be connected on digital bus, enabling multiple sensors to be read out independently via a single digital port.

A previous study examined the practical use of different temperature sensors to measure the temperature of surfaces in an outdoor environment[1]. The study found that plausible and traditional temperature sensor configurations may exhibit significant errors, and that digital temperature sensors can have practical performance on par with their analog counterparts. Here, we also make use of the observation that front surface temperature of a plate can be accurately measured on the backside, if the back is thermally isolated.

2.2 Emitting surface and heater

It is important to note that blackbody sources do not normally operate in thermal equilibrium; they contain a heat source, and net heat normally flows out of the reference surface through radiation, conduction and convection. In field (outdoors) operation, significant heat flow contributions can also come from the sun, wind, sky, fog and rain, the latter two with the added complexity of evaporation.

By shielding the blackbody, for example by enclosing it in a deep box, or inside a container or tent, it is normally easy to suppress the adverse effect of the sun, fog and rain. It is also possible to limit adverse effects of the sun by orienting the black surface away from the sun, and choosing a highly reflective surface on the sides and back of the emitter.

Some emitters feature pyramidal structures in order to let the multiple reflections along the pyramid walls enable an apparently higher effective emissivity. The disadvantage of using pyramids is that the effective emissivity differs at the tip and the base of the pyramids, all the more as the coating is typically diffusely reflecting the remaining light. In the case of significant wind or convection, the pyramid tips also tend to be cooler than the base. Both effects lead to a decrease in the effective radiance of the tips compared to the base, creating a regular pattern of residual radiance variation. A common way to limit this effect is to defocus the sensor observing the blackbody, but the patterning effect is still found to persist even when the blurred spot size is significantly larger than the pattern period. Another issue in the field is that the pyramidal structure easily traps dust and dirt, and is notoriously difficult to clean. Finally, it is also mechanically complex to fabricate the pyramidal structures with sufficient precision.

For all these reasons, we therefore avoid these pyramidal structures in the low cost blackbody emitters. Instead, we construct the emitters in perhaps the simplest possible way, from aluminum plates coated with commercial paint. It turns out that normal paints tend to have a quite high emissivity, often well above of 90%. Thus with commercial paint, anyone can make a fairly good emissive surface from locally available materials. It is important to note that since a thermal imager presumably is available, it is possible to check the emissivity of a particular surface coating by letting the imager view the radiation from a hot object reflected from the surface to be tested. Even with a coarse temperature calibration of the imager, and a coarse estimation of reflection geometry, a fair estimate of emissivity can be obtained. By coating a plate with patches of different candidate paints, it is possible to quickly identify the ones with lowest emissivity, either by viewing a reflection, or by heating the plate uniformly and imaging the emission. A distinct advantage of using a self-made painted-plate blackbody is that the emissive surface can be renewed easily and locally in case of wear, contamination and damage, which easily arises in practical use.

To obtain a homogeneous surface temperature, we attach a membrane heater to the back of the emitter plate. Such membrane heaters are readily available in a wide variety, at a low cost, since they are used as heater elements for 3D printer heated beds. These heaters provide a fairly uniform heating across their surface, and the shape of the emitter plate can be chosen to match the heated area of a heater with a desired size. The temperature sensor can be attached directly to the aluminum plate by cutting a hole in the heater (preferably in a way that does not alter the heater homogeneity significantly).

An emitter constructed in this simple fashion will inevitably have some limitations. Apart from emissivity, temperature nonuniformities can arise due to convection or wind, even if the heater is shielded from the weather. Heat transport estimates have shown that a 20 cm ×20 cm aluminum core plate will experience significant convection effects unless the metal is impractically thick.

A simple solution to limit the effect of convection is to orient the emitter surface horizontally. It is then possible to either look down at it from a higher angle, or look up at it from below. The latter solution has the advantage that it retains the heat better, for example if it remains inside a downward oriented container, whereas the first is a simpler solution where the emitter is simply put on the ground. A third solution is to erect the blackbody just prior to performing the measurements, and then perform the measurements before convection effects have the time to build up any significant temperature gradients.

2.3 Electronic controller

The Maker movement has led to a revolution in the development of electronic control in more or less complex applications. The most famous outcome is probably the 3D fused filament fabrication printer, in which a microcontroller coordinates the movement of a print head extruding molten plastic to build up three-dimensional structures layer by layer, according to instructions read from a memory card or a computer. One of the most successful microcontroller board families in use is the Arduino, for which a user friendly programming environment has been made available as free software. Code for many purposes is freely available. The effect has been an explosion in the use of microcontrollers to perform many tasks, with a popularization of its use in an ever growing community of users. This development has come together with the development of miniaturized, reliable sensors and effectors for mass markets, which enable sensing the environment, processing of the resulting data and actuating machinery to adapt to the processed signals.

In the case of the blackbody application, the microcontroller can read digital temperature data from the surface sensor, control the heater power (or duty cycle), regulate temperature and provide a user interface. All this is done using very low cost, standardized hardware and free software.

In our blackbody builds, we have used an Arduino microcontroller together with DS18B20 temperature sensors and a BTS432 power switch circuit[4]. Using a power switch and duty cycle variations to control the heat dissipated simplifies the electronics considerably, and provides for good efficiency, linearity and low heat dissipation. Given the large input tolerances from 4.5 to 42 V, the design is also easily scalable in terms of power dissipation requirements, for example when using different heater surfaces or surface temperatures. The software can be set to regulate the blackbody at a particular temperature, or to supply a constant power. For constant temperature operation, we use the Arduino PID regulator library. The user interface is a simple LCD plug-in module ("shield") for Arduino, which also has buttons allowing the user to adjust temperature or power setting. With the Arduino software suite and libraries, a wide range of functionalities can be implemented easily, depending on user preferences and the foreseen usage of the blackbody source.

We have found it convenient to operate our prototype blackbodies on battery power, so that they can be placed flexibly in a scene. For this, the basic Arduino Uno is well suited, since it accepts a wide supply voltage range, so that a blackbody can be run from readily available Li-ion batteries with 2 to 4 cells, as well as from a 12V car battery.

2.4 Mounting and cabinets

The introduction of microcontrollers has led to a tremendous fall in the cost of digital manufacturing techniques, such as 3D printing, and brought them within reach for anyone. For our project, we have experimented with printing cabinets for blackbodies. The most common 3D printing material, PLA, softens well below 100°C, but can be used to make cabinets for blackbodies intended for near-ambient temperatures. For higher temperatures, we have used commercial metal cabinets for electronics.

3. PRACTICAL REALIZATION

In this chapter, we present some results from our own experiments, illustrating the possibilities for low-cost fabrication of practically useful sources. We also discuss some possible directions for further development.

3.1 Homogeneous blackbody

One blackbody was produced with a rectangular heated surface of a 210 mm × 220 mm × 3 mm aluminum plate. The plate was spray coated with a commercial matte black spray paint, and a 5Ω heater mounted on a printed circuit type board was glued to the back of the plate. A hole was drilled in the heater PCB to make space for a Maxim Integrated DS18B20 that was glued to the back of the aluminum plate using thermally conductive silicone. The plate was mounted inside a metal cabinet in which a hole fitting the coated heated plate had been cut out.

Two different power supplies were devised for the unit, either a 230 VAC power supply providing 24V/6A, or two 12V $LiFePO_4$ batteries connected in series. The latter provided just over 120W for the heater, enabling it to sustain 100°C for approximately one hour, and even higher temperatures for shorter durations. Heat-up time to 100°C was less than 2 minutes, and the time required for cool-down to manageable temperatures, for packing and handling, was even shorter. Contrary to some commercial units, the cool-down phase does not require power, and the heater could be put inside the packing cabinet while still being hot, a feature that can be practical during field operation. The finished high-temperature blackbody is shown in Figure 3.1.

Given the high operating temperature, 3D printed PLA or ABS would not be suitable. Still, it could be mentioned that it would have been possible to 3D print the casing using high temperature plastics, such as Polyether ether ketone (PEEK) or polycarbonate (PC), which have glass transition temperatures at 143°C and 147°C, respectively, and are readily available as 3D printing materials.

Figure 3.1 Blackbody with homogeneous output, seen as a part of a kit (left) and free-standing (right). A display and a simple button user interface is seen lower right. As can be seen, there are two pairs of batteries in the kit. The charging time for the batteries is shorter than the operation time during one discharge at 100°C, so the blackbody could in principle be operated almost continuously on batteries.

The blackbody was mounted vertically and operated in a traditional way. Using a calibrated camera operating in the 3-5µm range, it was found that a 2.3°C gradient built up along the vertical axis when the blackbody was set at 100°C operating temperature. The blackbody was then placed horizontally to stabilize. After stabilization, the blackbody was mounted vertically and measured within seconds of being erected. At a 2 m range, the root mean square noise across the black body was then measured to be better than 0.1°C across the 0.04 m² surface, using a FLIR X6540SC infrared camera using 50 mm optics. It was found that exhaling in front of the black body when set at 100°C created a clearly visible image of the exhaled air, due to the increased amount of CO_2 present in the air. This test was repeated after the 2.3°C gradient had been reestablished, and the exhaled air was no longer visible in the auto-contrast camera video output, due to the increased dynamic range required to cover the heated surface.

3.2 Multi-source blackbody with 3D printed casing

Another source was built from two circular aluminum plates, 180 mm in diameter and 1.5 mm thick, again painted with commercial matte black paint. One of the plates has a foil heater applied to the back. Both plates have a DS18B20 temperature sensor attached in the center. The plates are mounted in a 3D-printed PLA casing, arranged such that one plate sits in a lid which flips out to expose the two blackbodies as shown in Figure 3.2. Each of the plates is backed by 20 mm of foam isolation to ensure that the back temperature is close to the front temperature. For the heated blackbody, the isolation also helps limit the power consumption. The heater is controlled by an Arduino Yun microcontroller board, which enables remote WiFi control and monitoring/logging of temperatures, utilizing functionality readily available in the Arduino libraries. The cabinet has room for battery and cables. For operation at low power, the unit can be conveniently powered for 12 hours or more by a small Li-ion battery pack.

The heated plate can be set to regulate at a fixed temperature, or at a fixed heater power. The other plate will have a floating temperature reflecting mostly the thermal ambient on the front side, due to the isolating foam backing. The cabinet is made from white PLA, to limit solar heat loading from the back. With a constant power applied, which is the mode we have used most, the two plates drift in temperature depending on the thermal ambient, but tend to maintain a constant temperature differential. Thus for thermal imaging at near-ambient temperatures, the dual source can be used as a convenient in-scene reference object, or it can be used for two-point nonuniformity correction of the camera.

Surface temperature was checked with an Exergen DX501 infrared thermometer. When the heated source is set 20 degrees above ambient, in still air indoors, the surface temperature is within ±0.5 degrees of the sensor reading, except in the lowest part, where a deviation of about -0.8 degrees is observed. The lower temperature at the bottom is probably due to convection cooling. The temperature deviations are roughly proportional to the overtemperature, so that for a smaller temperature differential between the two blackbodies, the nonuniformity will tend to be correspondingly less.

The emissivity of the paint was checked by measuring diffuse reflectance with an Agilent 4300 IR reflectometer. The results indicate an emissivity of 92% on average across the MWIR and LWIR bands, with some spectral structure in the LWIR band due to the paint constituents. This value is less than what would be desired for absolute temperature calibrations. However for measurement of relative temperatures, as well as for nonuniformity correction of cameras, the commercial paint surface should work sufficiently well.

Figure 3.2 Multi-source blackbody with 3D printed casing. Left: Front side with two blackbodies facing the sensor, one at ambient temperature (left side) and one with a foil heater (right side). The hinged cabinet can be closed so that the blackbody surfaces are protected during transport and storage. Center: Back side with a simple LCD display and buttons. On the side of the cabinet is the battery compartment opening. Right: Interior of the main cabinet, showing the foil heater and temperature sensor on the left, with foam insulation removed. On the right is the microcontroller with LCD "shield" and a board with the few extra components needed. Here the battery compartment holds a 7.2V, 5Ah Li-ion battery.

3.3 Possible extensions

We have under development a third type of blackbody, which is more unconventional. This source will have two heated plates coated with glossy black paint or powder coating, regulated at the same temperature. The plates will be arranged to form a wedge, with the black side facing inwards. One plate will be horizontal and the other will be tilted at an angle, typically 30-45° off-normal. Side walls will be formed by low-emissive surfaces, and the camera will be looking into the "jaw opening" formed by the two plates.

There are several reasons why this is a good idea. Firstly, with this arrangement, we expect to achieve low reflection by multiple reflections, akin to a Wood's horn beam dump, and thus a high emissivity. Second, a smooth surface is easier to clean, a fact worth noting for equipment used in the field. It is, however, desirable to avoid scratches, leading to a preference for a hard coating. Finally, for faster heat-up, it is possible to put a hinge on the two emitters, such that they heat up in close proximity with each other. In this way, heat is not lost to the surroundings before the source is needed. This may also speed up the required temperature rise at high operating temperatures. It may be necessary to alter the controller (PID) settings after the hinge is opened, but this can be easily detected by the controller using a micro-switch, so it does not represent a big issue.

It is interesting to observe that many digital temperature sensors can be connected to the same bus, easily enabling several tens of temperature sensors to be monitored simultaneously. As for the current control, ten or more heaters can be controlled from an Arduino directly, depending on the type of board. An Arduino Mega could control and monitor several tens of heaters simultaneously. This opens the possibility of tiling several heaters with a common controller. As an example, it should be possible to assemble a 6 × 8 tile matrix of 20 cm × 20 cm tiles, covering a 1.9m² surface. This could be powered by a 5kW power supply, or possibly a battery due to the short turn-on and stabilization time, and be able to be switched on remotely. To this could be added a large temperature monitored background with a large sensor array.

4. CONCLUSION

We have demonstrated the production of low cost, black bodies with useful emissivity properties, excellent homogeneity and scaleable design. This has been achieved through the use of 3D printer heat bed membrane heaters, low cost digital temperature sensors, modern manufacturing methods and consideration of basic thermal physics. The low thermal mass and efficient thermal management means such blackbodies can easily be powered using batteries, notably due to fast heat-up and cool-down transitions. The use of tiling enables the realization of fieldable, battery-powered (square meter-class) large surface blackbodies operating at up to or even above 100°C, and reference sources with controlled background emission. Blackbody sources of the kind described here can be constructed using readily available materials and tools, according to the needs of the user. With the use of locally available materials, the sources can also easily be maintained locally, for example for renewal of the surface coating. We believe that the simple concept described here can bring improved temperature calibrations to the rapidly expanding range of users of thermal imaging.

ACKNOWLEDGEMENTS

The authors would like to thank Mr. Hans E Torkildsen for helpful discussions during the development of this work.

REFERENCES

[1] Skauli, T., "Outdoor surface temperature measurement: ground truth or lie?" Proc. SPIE 5431, Targets and Backgrounds X: Characterization and Representation, (5 August 2004).
[2] Analog Devices technical documentation: http://www.analog.com/media/en/technical-documentation/data-sheets/ADT7420.pdf
[3] Maxim Integrated technical documentation : https://datasheets.maximintegrated.com/en/ds/DS18B20.pdf
[4] Infineon data sheet : http://www.datasheetlib.com/datasheet/171995/bts432-e2_infineon-technologies.html