Non-destructive high-resolution thermal imaging techniques to evaluate wildlife and delicate biological samples

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Abstract. Thermal imaging cameras now allows routine monitoring of dangerous yet endangered wildlife in captivity. This study looks at the potential applications of radiometrically calibrated thermal data to wildlife, as well as providing parameters for future materials applications. We present a non-destructive active testing technique suitable for enhancing imagery contrast of thin or delicate biological specimens yielding improved thermal contrast at room temperature, for analysis of sample thermal properties. A broad spectrum of animals is studied with different textured surfaces, reflective and emissive properties in the infra red part of the electromagnetic spectrum. Some surface features offer biomimetic materials design opportunities.

1. Introduction

Climate change and human population rise will increase pressures on natural habitats and species surviving in them. Monitoring wildlife may provide information to preserve at risk biodiversity. Until recently it was only the military who could see in complete darkness or through the heavy dust and smoke of battlefield conditions. In partnership with Paignton Zoological Park, and the Buckfast Otter Sanctuary, heat cameras demonstrate that endangered and vulnerable wildlife species, vulnerable directly to man's activities and also to climate change, may be evaluated in captivity without stress at a distance [*1*]. Stress is now a key zoological factor to minimize [2]. A Zoological Park provides a good test centre to evaluate animals from varied habitats, with technique applicable to environmental management and evaluation in the wild. We extend non-radiometric comparative visible, Near Infra Red (NIR) and heat photography [3,4] and comparative wildlife imagery [5,6] to concentrate on radiometric calibrated data. Heat cameras detect small radiated intensity differences from endangered animals protected in captivity day or night. We view animal behaviour and numbers where it would be difficult otherwise to do so. Although water absorbs heat so we cannot directly view *in-vivo* marine species marine mammals, e.g. Otters (**figure 1**) may be monitored at the water/air interface. Calibrated heat imaging is demonstrated over many species. Thermography offers safety advantages to zoo staff and researchers in the wild and aids animal condition diagnosis.

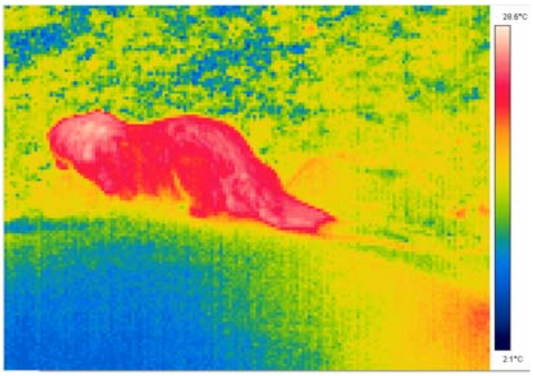

Figure 1 Otter

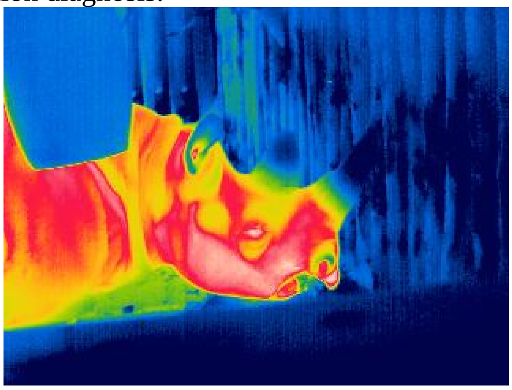

Figure 2 Black Rhino

2. Methodology

All objects above Absolute Zero emit heat. Radiated energy spectral distribution is proportional to T^4, in Absolute Temperature (T), and emissivity ε. Small temperature changes create large emission change. Objects with small temperature differences are easily detected if the animal ε is different to the background. Human skin has ε= 0.98, so just 2% of heat is reflected at the skin/air boundary. Many animals radiate heat efficiently allowing skin heat distribution detection remotely, without disturbing normal behaviour. Peak emission wavelength λpeak, is related to T: λpeak =2900/T in microns. Animals near ambient temperature have peak emission in the Far Infra Red. For most wildlife radiated power levels are unknown. A baseline of 'healthy' animal parameters provides diagnostic data before discussion of 'sick' animals. Although traditional 'contra-lateral' methods for non radiometric cameras have been used qualitatively and with success in animal [6,7] temperature data is quantitatively useful. As IR cannot be seen by eye, detected heat is converted to visible light. False colours represent different wavebands or Intensity levels. Colours are chosen to increase contrast for specific details otherwise missed.

2.1 Apparatus

For passive remote sensing we used a ThermaCam™ E320 camera (FLIR Systems ™) with a 320×240 pixel array sensitive to 7.5-13 microns, recording heat images. For active thermography Thermal Wave Imaging (TWI) used a flash thermography instrument, Echotherm™. Images were shot at high resolution (640×512) in the Middle Infra Red (2-5 microns). Multiple images were acquired 100ms after flash heating with an optical pulse. The light strikes a surface, briefly heating it. Butterfly surface temperature change is recorded as it cools by the IR camera.

3. Discussion

3.1 General thermal health

A healthy black rhino **figure 2** has a fairly isotropic surface temperature distribution. The body is covered with strong muscle tissue and thick skin plates. Insulation increases from birth so temperatures can drop 5°C in only 3 months. Ears and horns appear cool, near ambient background temperature and composed of dead chitin (hair) with no active blood supply. Millions of compacted hair-like fibres are reinforced inside with Calcium. Estimated radiated power levels using a simple cylindrical model approach where appropriate are given in **Table 1** for some species under study. Radiated intensity levels vary considerably between species, from the tiny leaf cutting ant to the elephant at over 13 kW**.** African elephants are big so overheating can be a thermoregulation problem in the wild, with high radiated powers.

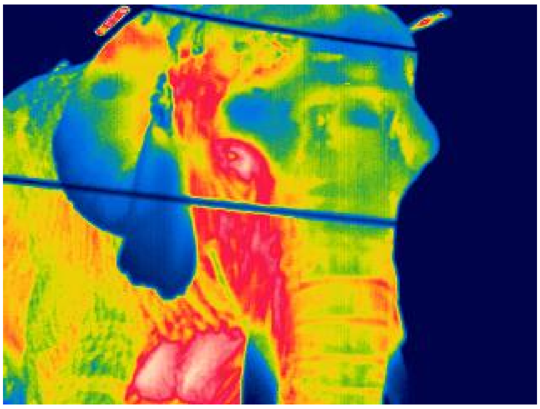

Figure 3

Ears permit large area evaporation. Cooling ears appear less hot than other parts **figure 3,** emitting a significant total power. Elephants cannot sweat as humans do and rely upon efficient heat transfer via ears. A hot trunk is seen alongside tusks at near ambient background temperature. The visible tusks are mostly dentine (ivory) with an outer enamel layer.

3.2 Contrast

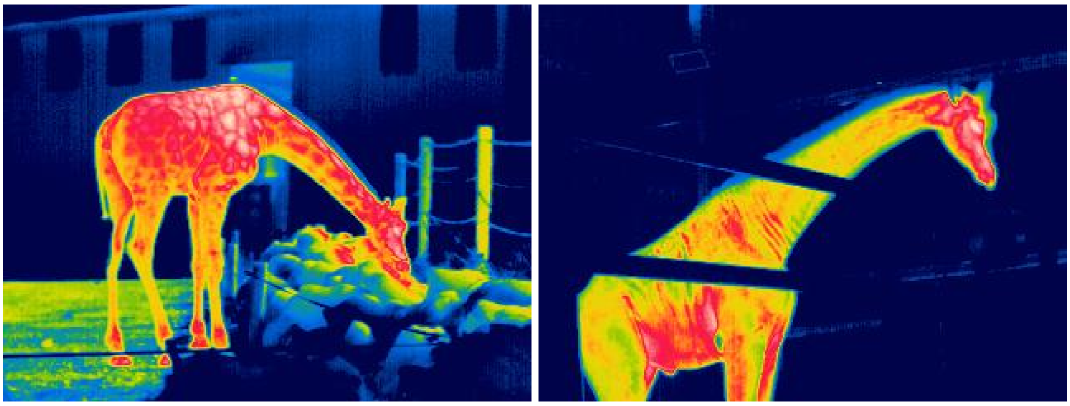

Figure 4a ***Figure 4b***

Day-time thermal analysis may reveal complex situations. Giraffe images (**figure 4a**), appear as if in military camouflage if imaged outside under strong sunlight. Dark pigments absorb visible and heat radiation. Pigments radiate heat from inside the animal and from absorbed visible light, as well as reflecting some thermal radiation. Dark visible regions appear 'brighter' in thermal imagery than visible lighter shaded regions which reflect light and contribute little to daytime heating. Without strong heating patterns aren't seen in the heat bands **figure 4b**. The same issue occurs with military camouflage, which must avoid heating through visible to heat conversion mechanisms. Darker brown regions have high emissivity and low visible reflectance- so brown regions absorb visible radiation and absorb/reradiate heat efficiently, giving the 'negative' of a visible image.

3.3 Pregnancy Section

A pregnant beagle bitch radiates more heat from its abdomen compared with a 2nd bitch believed by the Pack keepers to be pregnant but in fact served as a non-pregnant control (figure **5a and 5b** respectively). Radiometric cameras allow accurate evaluation of surface temperature of pregnant animals and importantly at an early stage of Beagle pregnancy (24 days) through to birth.

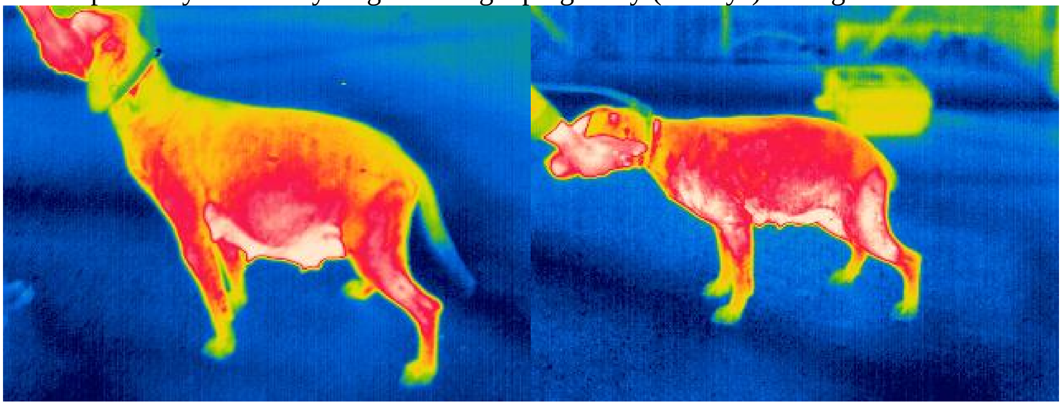

Figure 5a Pregnant bitch, 'localised' abdominal heating max. 34°C

Figure 5b non-pregnant control. Distributed regions of maximum temperature, max. 29°C

3.4 Analysis of butterfly wings

Recent biological structural research offers possible templates for future sensor systems. The Helena (Morpho) butterfly's blue iridescence for example results from light scattering from multilayer diffraction elements in intricate wing periodic photonic structures. Future man-made photonic and metamaterial periodic arrays will reflect some wavelengths while absorbing others. Pigments responsible for visible absorption usually absorb NIR. Iridescent feathers and butterfly wings result from physical photonics structure rather than pigmentation. However, little is known about the thermal properties of delicate layered biological structures. Passive thermography doesn't reveal much structural detail as there is limited material volume (thin wings) with low heat capacity, nor living 'blood' supply in wing specimens which are thus poorly contrasted against ambient background temperatures. Instead, a non-destructive TWI test for inspecting Space Shuttle wing leading edges to reveal sub-surface flaws and irregularities was used [7]. As a sample cools surface temperature is affected by internal structural flaws that obstruct heat flow, revealing detail. With TWI's Thermographic Signal Reconstruction method there is a significant increase in sensitivity and resolution, (Zebra butterfly wing **figure 6)** and for monitoring temporal changes. This technique will be valuable in shallow depth short range analysis of delicate biological specimens, but doesn't show live physiological or circulatory features. At thermal wavelengths surface interference effects seen in the visible blue aren't observed.

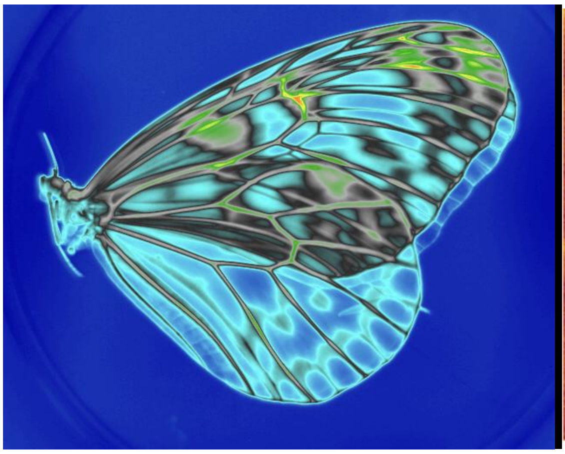

Figure 6 Zebra Wing

Figure 7

Figure 8

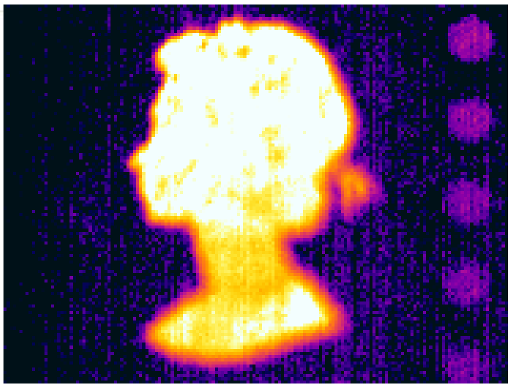

Figure 9

At high elevations some butterflies abandon flashy iridescence for light-absorbing brown to survive colder temperatures [8].Man-made photonics structures with constructive interference in the heat bands may be incorporated into spacesuits or desert garments to mitigate heat effects. Heat radiates into wings from the butterfly's body. Iridescence has no benefit at heat wavelengths. Butterfly photonic structures create modest visible 'blue interference flashes' but absorb heat poorly. Brown wings have greater light absorption yet weak thermal absorption, but light is absorbed generating heat. Recently hatched butterflies channel 'blood' into their wing structures initially in a non-uniform manner (**figure 7**) before developing small features of 'dragonfly' circulation loops in the upper wing surfaces revealed for the first time with thermography (**figure 8**). Appropriate lens combinations and choice of heat source can provide very fine-scale imagery of small object features, such as this heat reflective 'crown' on a 2nd class stamp (figure 9)!

Man-made materials with improved light absorption result in materials with increased thermal absorption. Man-made photonics structures may be designed to have low light absorption **and** low light to heat transfer. Depending on the thermal interference structure on the biochrome layer little or much heat may be reflected from designer surfaces. For example, a material with low thermal absorption at 10μm (FIR) having predominantly top and bottom surface reflections, requires only a $\lambda/4$ thickness to achieve destructive interference, i.e. 2.5μm. Artificial photonics structures, based on biological analogues may have applications in thermal wavelength filtering or design of compact Distributed FeedBack structures (DFB).

4. Conclusions

We remotely evaluate wildlife without stress in captivity, or in the field. Animals are undisturbed while passive thermal observation takes place, a benefit to animal subjects and keepers. Inter species radiated intensity levels vary considerably. Circulation loops are observed in the upper wing structure of live butterflies for the first time. Active thermal imaging reveals fine temporal detail at small spatial resolution. Designer man-made surface photonics structures may selectively reflect in a tailored fashion or create compact thermal filtering structures.

5. References

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Table 1 Wildlife thermal outputs

Animal	**Head θ/ °C**	**Body θ/ °C**	**Leg θ / °C**	**Power**
Rhino	30.5	25.5	23.5	3.7 kW
Sarus Crane	11.8	10.3	9.4	312 W
Elephant	21.1	21.1	20	13.4 kW
Camel	18.2	13.1	7.6	2.7 kW
Enoa	24.3	23.4	15.7	1.5 kW
Zebra	26.8	25.8	25.0	2.8 kW
Giraffe	23.1	24.7	13.9	5.3 kW
Leaf Ant	n/a	23.2	n/a	<1 W
Peccary	20.3	14.4	13.8	492 W