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Passive imaging of wind surface flow using an infrared camera

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HIGHLIGHTS

- Second-derivative temporal filtering on a thermal imaging video stream.
- Millidegree thermal dynamics show effect of turbulent air flow crossing a surface.
- Passive visualization of wind surface flow.
- Easy to implement for real-time view of flow dynamics.

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ABSTRACT

We present a method for passive imaging of wind motion against surfaces in a scene using an infrared video camera. Because the method does not require the introduction of contrast agents for visualization, it is possible to obtain real-time surface flow measurements across large areas and in natural outdoor conditions, without prior preparation of surfaces. We show that this method can be used not just for obtaining single snapshot images but also for real-time flow video, and demonstrate that it is possible to measure under a wide range of conditions.

Wind plays a large role in measurements taken outdoors, and yet its speed and direction can be quite difficult to measure. Visualizing the complex swirls and eddies created by turbulent wind patterns near the ground, and especially around objects, requires the use of a real-time imaging technique that is compact and capable of a wide field of view.

There are a number of experimental techniques commonly used for flow visualization [1]. While these techniques have been shown to work well, they generally require the introduction of contrast agents into the flow, or the use of controlled light sources, so that operating outdoors or analyzing the flow around large objects becomes difficult. Imaging smoke trails, for example, requires having a smoke generator and a structure for controlled releases of smoke streams. Schlieren imaging and shadowgraphy both require a spatially coherent light source in line with the imaging camera, and require a refractive index contrast within the flow. Planar laser-induced fluorescence imaging and Rayleigh scattering imaging are also popular methods, but require high-power pulsed light sources. And as in the case of imaging smoke trails, these methods require the introduction of a contrast agent – scattering particles or a fluorescent gas – in order to measure flow.

A passive method for measuring wind surface flow that requires only a single infrared video camera and simple video processing to implement thus provides access to measurements that are otherwise difficult to perform. This technique differs from most existing flow visualization methods in that it measures *surface* flow rather than bulk volumetric flow, a feature that can be an advantage or a detriment, depending on the application [2,3]. Inagaki et al. have previously demonstrated [4] the feasibility of infrared imaging of wind surface flow under favorable viewing conditions of strong thermal contrast between the surface and the ambient air, and of relatively smooth flow that allows for time-averaging to compose an image. We demonstrate in a series of experiments that not only is it possible to image in unfavorable conditions such as during light rain, but that it is also possible to obtain video measurements so that flow estimation can be performed in real time (up to 500 frames/s), for fast and highly turbulent flows.

The technique shown here of analyzing thermal dynamics of objects is closely related to thermal wave imaging [5] and pulse thermography [6], with the difference that, instead of being

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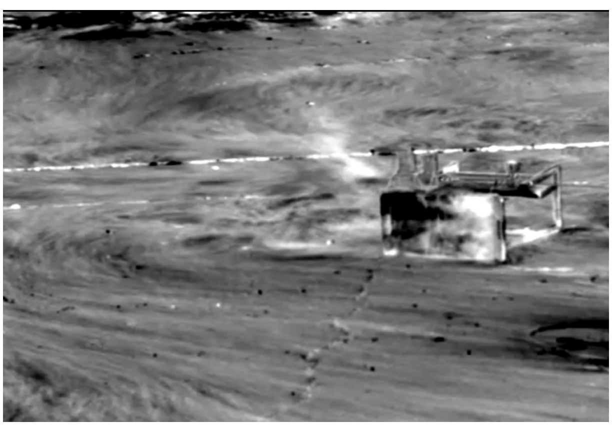
delivered by a controlled source, the “pulses” are uncontrolled and are delivered by the wind without active intervention by the viewer. By analyzing the temporal *changes* in the surface temperature rather than the temperature itself [7], wind turbulence becomes the contrast-inducing agent for visualization.

1. Analysis of surface thermal interaction with turbulent wind

Fig. 1 shows an example measurement processed for flow visualization, in which an infrared camera is looking out at a scene composed primarily of solar-illuminated concrete on a warm afternoon, with 35 °C air temperature, 75% relative humidity, and concrete at 50 °C surface temperature. The camera used for this measurement is an InSb detector array (IRCameras LLC, QuazIR SD) with a 640×512 image size, 20 μm pixels, and 14-bit output at 60 frames/s. The detector is cryo-cooled to 77 K and operates across the MWIR spectral range with a cold filter transmitting from 2.95 to 4.97 μm. The camera uses an $f/2.3$ lens (Janos Technology Inc., ASIO 50 mm) with a 50 mm focal length. With this configuration, the camera NETD is 15 mK (at 23 °C), and the integration time used was 2 ms. Faster readout rates can be achieved by cropping the image, up to the point where the integration time limits the frame rate to 500 frames/s.



Video 1

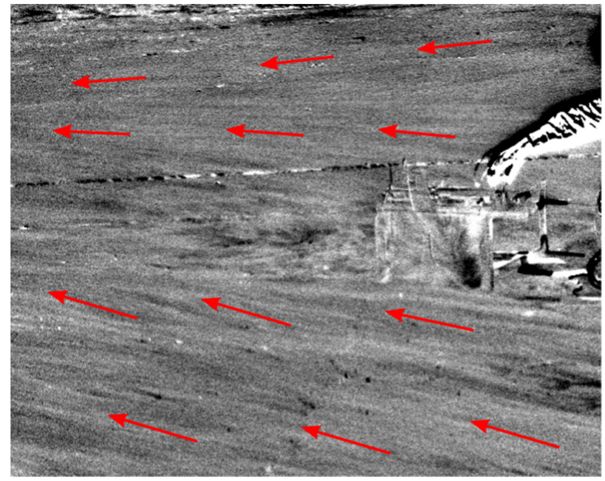


Fig. 1. A temporally-filtered image of a scene composed primarily of solar-illuminated concrete (see Video 1 in supplementary data). A colleague is adjusting equipment at the right side of the image, providing some context for the speed of the wind flow and the scene field of view. Red arrows have been added to indicate the local direction of wind flow along the concrete. The occasional dark and bright circles crossing the field of view in the video are due to insects flying across the field of view, seen as blurred circles because they are close to the camera and out of focus. In this image, as in Figs. 4 and 6 below, the filtered image grayscale display has been linearly scaled to black/white at brightness temperature differences of ±75 mK. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The data shown in Fig. 1 shows that when turbulent cool air passes across a warm surface, some surface regions are cooled more than others, due to differences in surface geometry, small temperature differences in the air passing over the surface, and to changes in the way that the air interacts with the surface. These small temperature differences decay over time as the heat conducts into the material beneath the surface, or a parcel of air with different temperature passes over the surface.

The striations visible in Fig. 1 are generally ~ 3 pixels apart from one another along their cross-stream (spanwise) dimension, which at this imaging distance of 8 m corresponds to a width of 12 mm. Because the concrete surface is observed at an oblique angle of $\theta \sim 75°$, the streaks appear closer together than they physically occur at the concrete surface, by a factor of $\cos\theta \sim 0.26$, so that the actual physical spacing across the concrete is about 46 mm.

In order to understand the physical phenomenon producing the striations we see in Fig. 1, we model the change in radiance viewed by the camera due to changes in temperature of an object in the scene and provide a simple model to analyze the dynamic thermal behavior of the imaged surface. The brightness of a surface in the thermal infrared is governed by the Planck blackbody law, mediated by the object's spectral emissivity and reflection of background light:

$$L_{\text{obj}}(\lambda) = \epsilon_{\text{obj}}(\lambda) B(\lambda, T_{\text{obj}}) + \rho_{\text{obj}}(\lambda) L_{\text{bkg}}(\lambda).$$

where $L_{\text{obj}}(\lambda)$ is the object surface spectral radiance, B is the Planck blackbody spectral radiance for an object with surface temperature T, ϵ and ρ are the emissivity and reflectivity of the surface (one can often assume $\rho = 1 - \epsilon$), and L_{bkg} is the background spectral radiance reflected from the surface. We ignore the small absorption and emission effects of the atmosphere between the imaged surface and the camera. Integrating $L_{\text{obj}}(\lambda)$ over the wavelength range of interest gives the total radiance, so that for a fixed background radiance $L_{\text{bkg}}(\lambda)$ and surface emissivity ϵ, the total radiance can be used to measure the surface temperature T. For all of the temperature data we present below, we will normalize effective temperatures to a reference emissivity of 0.95 – the measured emissivity of our blackbody, while also close to typical values for both concrete and unvarnished wood in the longwave infrared spectral region [8].

A surface exposed to a thermal gradient undergoes a change in temperature governed by the heat conduction equation, giving the surface temperature $T(\mathbf{r})$ as a function of the position $\mathbf{r} = (x, y, z)$ and time t [9]

$$\nabla^2 T(\mathbf{r}, t) = \frac{1}{\alpha} \frac{\partial T(\mathbf{r}, t)}{\partial t}, \tag{1}$$

for diffusivity coefficient $\alpha = k/(\rho c_p)$, heat conductivity k (W m^{-1} K^{-1}), mass density ρ (kg m^{-3}), and specific heat capacity c_p (J kg^{-1} K^{-1}). Representative values for the thermal properties of several materials are given in Table 1 for convenience, as these materials appear in the wind flow videos.

To simplify the complex thermal interaction between the fluid (the wind), the solid surface, and the boundary layer separating the two, we can consider rapid changes in the fluid motion as inducing impulse changes in the surface temperature. If we approximate the effect of the wind to cool or heat a surface over a short period as inducing a 2D Gaussian temperature profile across the surface, the temperature response of a semi-infinite solid object is given in a cylindrical coordinates solution as [10]