The Sightfield: Visualizing Computer Vision, and seeing its capacity to "see"

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Figure 1: **Seeing Surveillance and visualizing the capacity of a surveillance camera to "see"...** Leftmost: a linear array of computer-controlled LED lights is held in front of a surveillance camera. Even though the camera is concealed inside a dark dome with a shroud to hide any information about which way the camera is aimed, its sightfield may be visualized by abakography. An abakographic wand is moved through the space to trace out a "darkpainting" or "sightpainting" (inverse "lightpainting") that allows one or more abakographic cameras (e.g. one or more people wearing Meta-View Spaceglasses), to observe the surveillance camera's sightfield. This may be done by way of 3D (three-dimensional) AR (Augmediated Reality). The color change of the abakographic wand (from black to blue in this example) indicates, over time (animated from left-to-right), the surveillance camera's field-of-view and extent of coverage. (Self-portrait of author captured by a third remotely controlled camera.)

Abstract

Computer vision is embedded in toilets, urinals, handwash faucets (e.g. Delta Faucet's 128 or 1024 pixel linear arrays), doors, lightswitches, thermostats, and many other objects that "watch" us. Camera-based motion sensing streetlights are installed throughout entire cities, making embedded vision ubiquitous. Technological advancement is leading to increased sensory and computational performance combined with miniaturization that is making vision sensors less visible. In that sense, computer vision is "seeing" better while it is becoming harder for us to see it. I will introduce and describe the concept of a "sightfield", a time-reversed lightfield that can be visualized with time-exposure photography, to make vision (i.e. the capacity to see) visible. In particular, I will describe a special wand that changes color when it is being observed. The wand has an array of light sources that each change color when being watched. The intensity of each light source increases in proportion to the degree to which it is observed. The wand is a surveillometer/sousveillometer array sensing, measuring, and making visible sur/sousveillance. Moving the wand through space, while tracking its exact 3D position in space, makes visible the otherwise invisible "rays of sight" that emenate from cameras. This capacity to sense, measure, and visualize vision, is useful in liability, insurance, safety, and risk assessment, as well as privacy/priveillance assessment, criminology, urban planning, design, and (sur/sous)veillance studies.

1. Introduction/Background

Many devices around us are being fitted with computer vision systems. Devices that were once "blind" now "see".

Recently, computer vision systems have been installed in many toilets and handwash faucets in various public buildings, to flush the toilets and turn the taps on and off automatically. Early vision systems of this type merely used a single element sensor (e.g. as a 1-pixel "camera"), but more modern systems use more sophisticated active vision systems with sensor arrays.

The pixel count is small – on the order of 128 or 1024 pixels – not enough to identify faces or "suspicous activity", but sufficient to reliably flush a toilet or control a faucet. As stated by one of the manufacturers:

> "... instead of simply detecting the presence of an object, controller ... based on the signals received from the camera identifies the object type, the presentment, and adjusts valve ... accordingly" [U.S. Patent 8,162,236].

Faucets with the 1024 pixel camera and structured laser light and HOEs (Holographic Optical Elements) are able to recognize gestures and distinguish the difference between a toothbrush, hands, or dishes being washed in a sink using

3D Kinect-like sensing technology (U.S. Patent 8355822). Gesture-sensing shower facilities are also in widespread use, such as the Rada Sense digital showers installed in all of the shower areas of the Millennium Stadium changing rooms.

These forms of "liquid surveillance" were developed originally for use in prisons (e.g. Sloan Valve's "Sloan Monitored Systems") to monitor and control AWL (Air, Water, and Lighting) from a central location, but they have now evolved into widespread use in many commercial and consumer electronics efforts. Such systems raise a number of possible issues such as Privacy and Trust (e.g. when data is inadvertently disseminated), and the like, and Trust as a computational concept [37, 38], as well as performance issues (such as possible water waste or flooding if the system malfunctions).

Many new LED (Light Emitting Diode) streetlights have built in cameras that sense people, and dim the lights or turn them on or off automatically in accordance with usage patterns (e.g. "Pixelview" by Lighting Science Group, "Netsense" by Sensity Systems, "Lumimotion" by Philips, and "Intellistreets" by Illumination Concepts). The cameras in the Philips Lumimotion lights typically do nothing more than sense occupancy, but the cameras in the Sensity LED lights also recognize faces, license plate numbers, and "even identify suspicious activity, sending alerts to the appropriate staff"[6].

Embedded vision sensors are being used for people-counting in offices, washrooms, classrooms, and the like [12] which provides great promise in energy and resource savings, e.g. by adjusting AWL (Air=HVAC, Water, and Light) to meet the needs of the occupants without waste.

There is an obvious need to understand what such systems can sense, what they can "see", and how well they perform. Regarding matters of privacy, we may wish to ensure that certain things are *not* seen, whereas regarding matters of public safety, efficacy, energy savings, etc., we may wish to ensure that certain things *are* seen or sensed.

Thus there is a need, thus far unfulfilled, to be able to see, measure, understand, visualize, etc., vision itself.

Within the world of embedded vision systems, the field-of-view of a camera may take various forms such as a flat planar "sheet" (e.g. as in the example of the linear-array cameras used in washroom fixtures), or a rectangular pyramid, as is typical of a vision system using a two-dimensional sensor array. Many vision systems use a fish-eye lens, which can be "de-warped" in real time [9], and thus their fields-of-view may assume a variety of different forms, depending on post-processing.

The field of embedded vision has recently expanded greatly; see recent work by Goksel Dedeoglu and collaborators on optimized vision libraries [10] and active gesture sensing [11], and related work by others in Augmented/Augmdiated Reality (e.g. Project Tango, and its work by Johnny Chung Lee, EVW2014, "Embedded Vision Challenges for Implementing Augmented Reality Applications", Peter Meier, EVW2014, and many other works being presentd at IEEE EVW2014).

1.1. Surveillance and Sousveillance

Computer vision may be divided into two categories:

- surveillance: cameras on fixed objects, such as property (e.g. land or buildings); and
- sousveillance: cameras on people, e.g. by way of wearable cameras, and, more generally, wearable sensing, "quantified self" (http://en.wikipedia.org/wiki/Quantified_Self), and the like.

The primary (#1) definition of **"surveillance"** is:

1. "**a watch kept over a person, group, etc., especially over a suspect, prisoner, or the like**: *The suspects were under police surveillance.*" [1]

The word "surveillance" comes from the French word "veillance" which means "watching" and the French prefix "sur", which means "over", "above", or "from above". Thus "surveillance" means "to watch from above" (e.g. guards watching over prisoners or police watching over a city through a city-wide surveillance camera network). The closest purely English word is the word "oversight". Surveillance often consists of cameras affixed to property, i.e. real-estate: either buildings (e.g. mounted to inside or outside walls or ceilings), or to land (e.g. mounted to lamp posts, poles, and the like) [32, 40, 5, 19, 42, 3]. In this sense, surveillance is typically initiated by property owners or property custodians such as governments.

A more recent phenomenon, sousveillance ("undersight") refers to the less hierarchical and more rhizomic veillance of social networking, distributed cloud-based computing, self-sensing, body-worn vision systems, wearable cameras [36, 32, 33, 46, 19, 40, 23, 3], and ego-centric vision (i.e. Personal Imaging) [29, 27, 41, 28, 24, 14, 47].

Surveillance [26] and Mobile Pervasive Sensing [4] have emerged recently as fields of study. Sousveillance (e.g. social networking) is also an important area of study regarding privacy, security, and trust [22].

The term *veillance* is now used, more broadly, to describe a politically-neutral watching or sensing that does not necessarily involve a social hierarchy [7, 8]. We seek to measure, sense, display, and visualize veillance, regardless of whether it is surveillance or sousveillance.

Whereas visualization systems are commonly used for network security [44], data threat analysis [2], and the like, there appears to be no prvious work on spatial visualization of veillance (computer vision or sight itself).

2. Visualizing Vision and Seeing Sight

The present work on visualizing vision combines two fields of research: (1) veillometrics; and (2) abakography and wearable computational lightpainting with AR-based abakography.

(1) Veillometry: In recent work [23] we have developed a simple physical and mathematical framework for quantifying and measuring camera veillance, in terms of *vixels*, *veillance intensity rate field*, and *veillance flux*, which, when crossing borders (surfaces) of authority, can measure the relative amounts of surveillance and sousveillance in a physical area or point in space.

(2) Abakography: We have also developed new methods of data visualization using long-exposure photographic methods known as abakography [35].

Abakography may be done in conjunction with wearable computing and wearable computational lightpainting, so that vision can be visualized through Digital Eye Glass [35]. Whereas AI (Artificial Intelligence) is an attempt at emulating human intelligence using computers [39], wearable computing is based on HI (Humanistic Intelligence) which attempts to merge humans with computers so as to create intelligence from the human being in the feedback loop of a computational process [30].

A camera may be regarded as a time-integrating device. It integrates light, over time, at each pixel, or at each point on a film plane, to form an exposure. In this sense, a long exposure shows the time-integral of the energy of the light received, at each point or pixel. Long exposure photographs show traced patterns of light sources, known as abakograms from which may be derived their abakographs [35]. The words abakograph and abakogram derive from the Hebrew word "אבק" ("abaq") meaning "dust", the same root of the word "abacus", from Greek "$\alpha\beta\alpha\xi$" ("abax") meaning a surface covered in sand or dust for doing calculations or drawing mathematical figures. The metaphor for abakography/avakography/avakorgraphy (אבק-וגרפי or אבקאורגרפי) is also one of beads on wires, much like the modern (i.e. with wires rather than sand) abacus.

A plurality of light sources, moved together, can be made to operate like a dot-matrix printer, i.e. to create text, graphics, and other patterns in three-dimensional space. An array of light sources, equipped with appropriate sensors such as IMUs (Inertial Measurement Units), and used with vision-based tracking, forms the abakographic visualizer [35]. This enables the sightfield of a camera to be visualized using another camera, as shown in Fig 2.

DEG (Digital Eye Glass), such as the Spaceglass shown in Fig. 1, may be used as the abakographic camera (in this case a sousveillance camera) to capture in 3D, time-integrate, and display the resulting sightfield to a user of the DEG. Devices such as Spaceglass can detect hand gestures, so a user can draw, point, and select by pointing in mid-air. By seeing a 3D abakograph in augmented/augmediated-reality glasses [48, 16, 17, 15, 45, 34, 18, 29] it is also possible to "draw" an abakograph as a tangible object that can be grasped and held in 3D space. In this sense, the sightfield becomes a tangible object that the user can experience as if it were real, thus grasping, touching, holding, and visualizing vision itself.

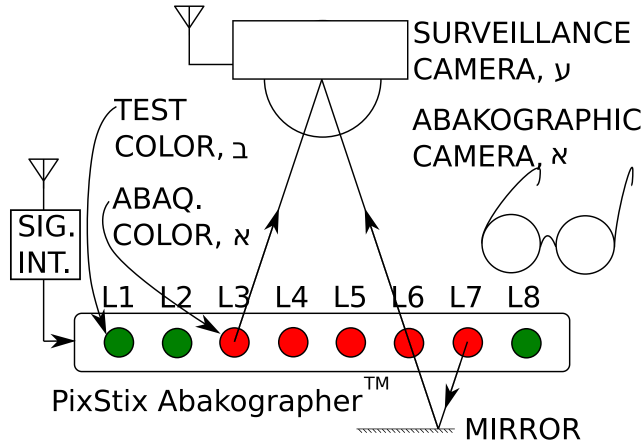

Figure 2. Visualizing Vision (Seeing Sight) by way of abakography. A PixStix™Abakographer™is swept through space like a wand. Typically there are hundreds of light sources along its length, but for simplicity, only 8 are shown here, numbered L1 through L8. Here the lightfield test color, ℶ, is green. When the lightfield falls within the sightfield of a surveillance camera, the color changes to the abakographic color, ℵ, which is red in this example. A second camera, the abakographic camera, captures the abakograph of the wand, to build up a representation of the sightfield over time. The "PixStix Abakographer contains a processor to present a special pattern, while sensing changes in response to nearby surveillance cameras. It has 3 modes of operation: (1) user's own surveillance camera (e.g. a WiFi camera with known login information; (2) a presumed hostile or uncooperative camera (hence the signals intelligence module named SIG. INT.), or (3), a proposed (not yet installed) camera (e.g. a shopkeeper wishing to decide how many surveillance cameras to purchase for a future installation). When the surveillance camera responds in some way, the color of the lamps to which it responds are set (proportionally) to ℵ (e.g. red, with intensity proportional to response) to mark the presence (and strength) of vision. Otherwise the lamps are set to ℶ (e.g. green). Thus, with video feedback, the abakographer is "swept" through the space that is under, or suspected to be under surveillance, thus "painting" in the sightfield of the camera. Note the possibility of reflections in the sightfield, e.g. by way of a MIRROR or perhaps reflection off a shiny waxed or wet floor, which causes lamp L7 to change to color ℵ (e.g. red).

3. The Sightfield

In 1846 Michael Faraday proposed the concept of a lightfield, i.e. that light should be regarded as a field, like electromagnetic fields that Faraday had also been studying [13]. The term "light field" was coined by Arun Gershun in 1936 [20]. Lightfields have recently been applied to computational imaging [25].

The author has proposed "lightspace", the tensor outer product of the lightfield with itself, as a way of capturing how scenes or objects respond to light [43]. Abakography is based on this tensor outer product of the lightfield with itself. See Chapter 5 of [31].

I wish to introduce the concept of a "sightfield" as a time-reversed lightfield, i.e. a "darkfield" in which cameras are in some sense the opposite of light sources.

Consider the following table, in which we juxtapose "hot" with "cold", etc.. "Cold" does not exist and is merely the absence of heat, yet "cold" is a useful concept. Likewise, in electronics, the concept of the absence of an electron (called a "hole") is also a useful concept. In 1941, Stueckelberg postulated the concept of a time-reversed electron, the *positron* [21].

Light travels from subject matter (e.g. scenes and objects) toward cameras, our eyes, and similar sensors. But in the field of Computer Graphics, it is often more convenient to perform *Ray Tracing* in reverse: from the camera out toward the various scenes and objects. This conceptualization of the camera, as an emissive device, is reminiscent of early theories of human vision (i.e. that the eye emitted light in order to see, fifth century BC, by Empedolces, and 4th century BC by Plato).

The author has proposed the "scoton" (etymologically correct Greek opposite of "photon") as the opposite of a photon. The "sightfield" is thus, similarly, the opposite of the lightfield, and may be regarded as a time-reversed lightfield.

Presence	Absence or Time-Reversal
Hot	Cold
Heat	Coldness
Electron	Hole or Positron
Photon	Scoton ("Darkon")
Lightfield	Darkfield or Sightfield
Lightpainting	Darkpainting or Sightpainting

The sightfield is a useful concept and makes the operation of a camera consistent with everyday understanding of it as emitting ("shooting") something, e.g. cinematographers "go out on a film shoot", and the "film magazine" (like the magazine of a machine gun) is said to capture a "great shot".

The sightfield is made visible by "darkpainting" or "sightpainting" i.e. the opposite of "3D computational lightpainting" (abakography, etc.). See also, the concept of "veillance flux" [23].

4. The three veillometric scenarios

There are three ways in which a sightfield may be visualized, i.e. in which veillance measurement may be combined with abakography, using an abakographic user-interface as a display device to visualize vision and determine+display the quantity and quality, position, field-of-view, etc., of veillance in 3D space:

1. a "friendly" camera that we control;
2. a hostile camera that is controlled by another entity, to which we may apply signals intelligence to receive its signals;
3. a camera we can't receive signals from, possibly because it does not yet exist (e.g. for a proposed situation).

Scenario (1) may arise, for example, if we wish to visualize the sightfield within our own building, perhaps for insurance or risk assessment purposes (e.g. to show an insurer that our surveillance system provides complete coverage).

Scenario (2) may arise, for example, when someone is spying on us through hidden veillance, or when the veillance camera is visible but the feed from it is hidden. Surveillance cameras are often "conspicuously concealed" in dark smoked acrylic or plexiglass domes with black metal or black plastic shrouds that hide the direction of the camera's gaze. The surveillors want us to know we're being watched but want to hide which way the camera is looking. However, we might still apply Signals Intelligence methodology to receive a signal from the camera, or at least to determine when the camera evokes some response, without necessarily being able to decode the entire image content.

Scenario (3) arises when we are unable to do so, or when the camera does not exist yet. For example, if we wish to visualize a proposed sightfield in our building, to help in the selection of a surveillance system, or in determining if the cost of the system is justified by the savings it will produce. In this case, we merely affix a small wireless camera into the space in alignment with the existing (unreadable) or not yet existing (i.e. proposed) camera/camera-location.

Scenario 2 involves the creation of a "video bug sweeper", analogous the audio "bug sweepers" used to detect hidden microphones. An audio bug sweeper demodulates radio signals to baseband audio, amplifies the signal, and reproduces it in a loudspeaker to induce feedback and thus "squeal" in the presence of a bug.

The bug sweeper is swept through various permutations of space and frequency and demodulation scheme.

The proposed video bug sweeper uses the abakographic wand which resembles, in some sense, a "pushbroom" that can be swept through space to reveal a sightfield.

The abakographic wand is programmed to flash patterns of light that test for veillance, i.e. for some response to the patterns that can spatialize the sightfield.

In this way the sightfield manifests itself as the abakographic lightfield.

By "painting" with a test color or test pattern, a response manifests itself and is sensed, for which the abakographic

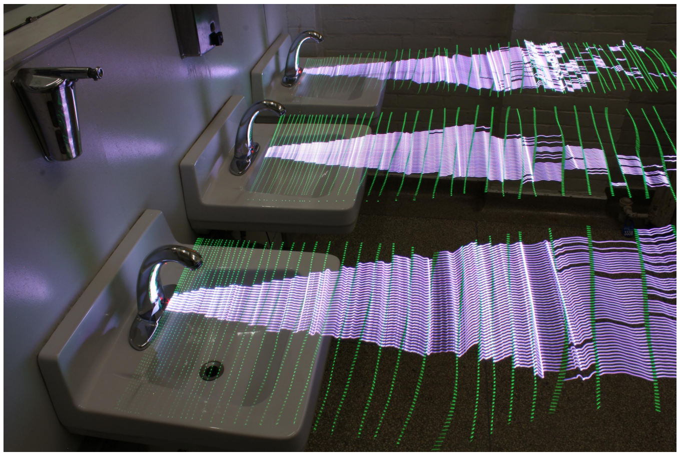

Figure 3. **Visualizing Computer Vision and Seeing How it "Sees"**. Abakography used to indicate spatial extent and view of the sightfield from faucet sensors. Note some degradation of the sightfield farther away from the sensors. Here the test lightfield, ב, is indicated by green, and the sightfield, א, is indicated by the color white.

wand displays an abakographic pattern (different than the test pattern). Alternatively, the 3D position and orientation of the abakographic wand is sensed by other means, and the sightfield may be generated in an entirely synthetic way.

In the former case, green is typically used as the "test colour" because most digital cameras have twice as many green pixels as red or blue (due to the Bayer pattern, red, green, green, blue), and also because most cameras are more sensitive to green light than other colors (due to the fact that the green channel is mid-spectrum and also to match the sensitivity of the human eye). The test color is denoted ב (i.e. the first letter of the Hebrew word for "test", as shown in Fig 2).

An abakographic colour, such as blue (as in Fig 1), or red, or white (as in Fig 3) is denoted א (first letter of the Hebrew root of "abacus", i.e. "abakography"), as indicated in Fig 2.

The color א indicates detected veillance, to the abakographic camera, when the ב colour is detected through the veillance camera. When this happens, the abakographic wand displays the color א to indicate where veillance is sensed, so that the sightfield can be built up over a time-exposure.

In some sense the apparatus may be thought of as a video feedback loop, between the abakographic wand and the veillance camera, with the processor in the wand entering an infinite loop to keep stepping through light patterns, and sensing the response thereto.

As examples of sightfield visualization, see Figs 1 and 3.

5. Conclusions

The concept of visualizing vision (i.e. seeing the capacity to see) has been proposed and presented. In particular, computer vision systems may be sensed, measured, visualized, and explored, in terms of their sightfield.

An implementation of a sightfield visualizer system was presented, based on abakographic image processing, using an embedded microcontroller with a second camera to capture a sightfield from a computer vision camera.

The device may be used co-operatively, e.g. by a user or owner of a surveillance system to visualize the efficacy of their own cameras, or un-cooperatively, as a video "bug sweeper" which uses video feedback to detect hidden video surveillance or sousveillance.

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