VISION OF HUMANS AND MACHINES

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Abstract

First, we explain the generic meaning of vision or seeing. Then, we discuss the features of human visual system, and contrast it with vision of some animals. We describe a \n infrared camera to make visible what is not visible to unaided human eye; and an interferometric system to detect a planet outside our solar system.

1. Vision and seeing

Vision is one of the most important senses, while at the same time this sense is also able to process and discard the largest amount of information per unit time. One of the ways it compresses the information is in mapping from 3-dimensional space to 2-dimensional surface. Thus, one dimension is "lost". Most optical instruments try to supplement, expand and/or imitate aspects of the human vision, the crowning glory of the engineering in nature.

1.1 Vision as a sense

We value our ability to see the environment as a special and dear gift. In fact, of all five senses vision takes the second largest area in the brain, right after the touch and skin. Most of us consider the vision our most important sense, because it allows us to orient ourselves within the environment, permits us to plan the responses to it, and allows us to build small tools and to read the instructions. The visual system includes two eyeballs, where an image is formed and detected by special nerve ends, optic nerve, and the visual cortex in the brain.

Sometimes the eyeballs are deformed, elongated or shortened, so the image is formed either before or behind the retina on the back wall. This small defect is easily corrected with prescription lenses. The performance of the eyeball is nowadays quite well understood, and imitated by most simple optical instruments.

1.2 Optical instruments

A photographic camera exactly imitates an eyeball, except that it is not made of a living tissue. Its image is permanent only after the film has been developed and fixed. A magnifying lens is like one imaging element in an eyeball without the retina. It does not even form a a real image on any surface image and it incorporates no detecting elements. A microscope is just a complicated magnifying glass that actually forms an image, but without the detecting elements. A telescope is a huge eyeball, without a detecting element. In both of the last two instruments, we use our eyeballs to help them see, other times we use a photographic film or a charge-coupled device (CCD) to record the image.

1.3 Mapping from space to a plane

Every eyeball, either that of an animal or of the machine, performs a simplifying function. It maps a scene in a three-dimensional world on a two-dimensional surface (often a plane). This generates two problems. All the objects in the scene appear to be in the same plane. Additionally, the eyeball includes a number of surfaces that bend (refract) the light rays in such a way as to form an image on the retina. We can only get a sharp image for the objects located in the same plane.

1.4 Vision as intelligent information processing

We say that a girl sees a mouse, when the following conditions are met:

1. the mouse is in front of the girl;
2. the mouse is illuminated with the visible light;
3. the light, reflected off the mouse, is incident into the pupil of the girl's eyeball;
4. the girl's imaging lens forms an image of the mouse on the retina;
5. some photons reflected off the mouse are absorbed in the nerve ends on the retina;
6. this absorption causes an electro-chemical change in the nerve ends;
7. the nerve sends an impulse to the brain;
8. the brain combines many such signals from many parts of the mouse;
9. the brain calls on the memory to ask whether such object has been seen before;
10. the brain identifies the object as a mouse and tells her other things about mice that it has stored and has retrieved;
11. the brain tells the girl that there is a mouse in front of her;
12. another part of the brain, where emotions are residing, tells the girl that this is a great time to start screaming.

The scream represents the confirmation that the girl has seen and correctly identified the mouse.

2. Human visual system

Human visual system is a highly versatile, multifunctional, and complex set of organs, working mostly without relying upon user's instructions, input, processing, or understanding. It detects and processes visible light. In addition, it can distinguish very small features, such as letter on a printed page, and detect motion anywhere within half a sphere. Motion is just a small change in a scene with time. In terms of sensitivity to the light input signal, it has an unprecedented dynamic range of 10^{16}. It has the ability to adaptively bring to focus objects far away and as close as 4 inches (10 cm).

Humans are able to assess object distance due to the stereo disparity (two eyeballs) and by learning to recognize and identify the depth cues. Finally, vision is a learnt process and requires direct interaction between scene, object and feature identification, and confirmation of correct interpretation. Vision involves pattern recognition algorithms, storage in memory, retrieval from memory, and broader associative memory. The brain uses all the information, the stored one and the new one, to make sense of the environment and to make "intelligent" decisions about what to instruct the body to do next. Sometimes, the brain even involves the conscious mind in this process.

2.1 Visible light

Human visual system may be described by its special features. It detects the light within a narrow spectral band of the electromagnetic spectrum, from about 400 nm to about 800 nm, called visible light. The rattlesnake can detect light also in infrared, the light that is not visible to us, with the wavelength longer than that of red. This light was discovered about 200 years ago by humans.

2.2 High- and low-resolution vision

Humans have two different light receptors, cones and rods. Cones are used when the environment is bright, during the daytime, to see colors, to read, and to perform other detailed visual tasks. The fovea includes cones only. Font 12 in the print is legible to a large population. Rods are used at night, they cannot distinguish between colors, but they can detect moving object. When the fovea is severely damaged, the letters have to be made several times larger. The mongoose (in the Jungle Book by Kipling) is biologically adapted to functioning well in low-light levels. He comes out at night, and his vision is very sensitive to motion. Even a rapid strike by a snake does not surprise him.

2.3 Large and small field-of-view

The human eyeball is equivalent to two cameras, of which only one works well or both work adequately at the same time. The first one is low resolution, enormous field of view (bigger than that of a planetarium or E-MAX screens), sensitive to individual photons (packets of light) in a healthy young man, adapted to complete darkness. The second one is high resolution, huge light levels (10^{16}), half a degree field of view (size of a letter at 10 inch standard recommended reading distance). The first autonomous vehicle sent to Mars, that humans deployed into space and that recently left the Solar system, carried a high-resolution and a low-resolution visible camera.

2.4 High- and low-brightness vision

Two characteristics contribute to human's adaptability to enormous range of light levels. The diameter of pupils changes automatically depending on the illumination levels and the preferred sensitive elements may be chosen. When a person is not well mentally, pupils do not perform normally.

2.5 Adaptive vision

One of the refracting optical elements inside the eyeball is called lens, because of its shape. It is very weak in terms of refracting power. However, it can flatten its shape when we look at the distant objects to bring them to focus on the back surface of retina. This function also is performed by our brain without our instructions. Only within the last few years have machines succeeded at changing their surface shape using mechanical and electro-optical actuators.

2.6 Stereo-vision

A decision needs to be made about the distance of the object from the observer. Some objects are partially obstructed. Here it is highly advantageous that we are equipped with two eyes, even though many people function incredibly well with a single eye. Two eyes, separated by about two inches see two images of the world, slight different, because of their different points of view. This disparity is used by the brain to calculate the distance of the objects and is referred to as the depth perception. This means that the brain does things on its own that we do not "know" how to do or how to direct the brain to do it. This function can only be performed when a person has true bi-ocular vision, and both eyes participate in vision. Imagine the depth perception skill of the mountain goat, hopping from one ledge to another! If it is born with one defective eye, it serves the universal purpose of providing the meal for the predators. We try to give machines the same skill, by having them look at the same scene from two different orientations.

The human brain has developed other techniques of measuring, determining, and assessing the distance in addition to the stereo-disparity. We call them cues and they are dependent on environment, culture, and are therefore learned.

2.7 Intelligence in vision

The fact that we can learn makes us refer to ourselves as being intelligent. One of the first cameras to be made intelligent has been used for interplanetary navigation in a recent *Cassini* mission to the outer planets. A CCD camera was equipped with memory of the star distribution (fixed in the inertial coordinate system) and was taught to think and to recognize stellar patterns by equipping it with a unique algorithm. This allowed the autonomous vehicle to correct its path just by looking around at the stars. Navigation by stars was one of the most important secrets to accomplish trade with the Far East, making rich primarily the naval powers.

The crowning glory of the visual systems of high level animals, including some dogs and humans, is the ability to recognize an image, some of its geometrical transformations, and even a partially-hidden. It is now believed that a prototype human, a baby, needs to be taught important functions in vision at the right age or he fails to develop appropriate vision skills.

A baby first learns to recognize the oval shape, corresponding to the shape of her care-taker's face. At about 11 month, the baby needs to learn to focus on near objects with both eyes at the same time. Then, the child learns to use the stereo-vision effortlessly playing with and manipulating small objects.

3. Infrared vision and cameras

When the scientists discovered that the light includes other colors (wavelengths) in addition to the visible ones, the engineers found the way to use them. Radio-frequencies are used for radio broadcast, x-rays for medical and dental diagnostics, microwaves for communication and cooking, infrared for analytical chemistry, diagnostics, weather predictions and astronomy.

Our Sun emits a lot more energy in the infrared part of the spectrum than in the visible. It acts as huge heater, and keeps Earth comfortably warm to keep the Earthlings alive. The ordinary incandescent bulb emits mostly infrared light, which we can detect as heat just by touching it (actually, we can even get burnt by it). The so-called fluorescent light generate "cold" light and are preferred for energy conservation.

In the last century, the scientists discovered several materials that may be used to detect infrared, and even change it into electrical signal. This opened the possibility of building the infrared cameras that now are available in several bands and with large number of pixels, 1000 x 1000. We are used to light and dark in the visible light. These concepts have acquired a new meaning in the infrared. Dark in the visible usually means lack of illumination or shade. Figure 1 shows an infrared image of a parking lot taken at night. One car is leaving on the left. It is dark on the top, because the night sky is cool. There are parallel lines on the parking lot, indicating that there were car parked there during the day, so the sun did not warm up the ground. We could call this a latent shade. The edge of the parking lot is surrounded by a pavement, which is still hot and bright. This is a different image of the world, but very informative in its own way.

Fig. 1. Heat shadows of cars on the daytime parking lot are still visible in the middle of the night in infrared light.

4. An interferometric system to detect a planet outside our solar system

Possibility of extra-solar planets holds enormous fascination for humans. Maybe we find some form of (intelligent) life out there? We sure could use some advice! The planet detection problem involves many scientific, engineering, and technological issues.

After flying by, dropping probes, and even landing devices on most planets within our own solar system, the search for extra-solar planet is included in every proposal to either build a larger and better earth-, space-, or moon-based telescope, or observatory facility. Some large diameter telescopes have been proposed. However, according to the basic Rayleigh resolution criterion, the telescope diameter does not help in seeing a faint planet. According to this basic principle, two point sources have to be separated adequately so that peak of one falls into the minimum of other.

The star is so bright that its minimum is brighter than planet signal. Thus, an imaging, eyeball-like instrument will not do to see the planet either in visible or infrared. Our Sun emits 10^9 times more photons at its peak of emission and 10^5 times more photons at the peak of emission of the most radiant planet, Jupiter, in infrared. An aperture of unit area collects only 15 photons per second originated at Jupiter-like planet at a distance of 10 parsec in the 1μm wavelength interval and 1.2×10^6 photons from the star.

We proposed a rotating rotationally shearing interferometer in infrared to detect a planet, should there be one. We built a proof-of-concept instrument in the laboratory, for the operation in the visible. Its photograph and the schematic layout is presented in Figure 2. The next step is to build a prototype that works in infrared. This will be much more difficult as we do not see at those wavelengths. However, we welcome the challenge and we are confident that we can do it!

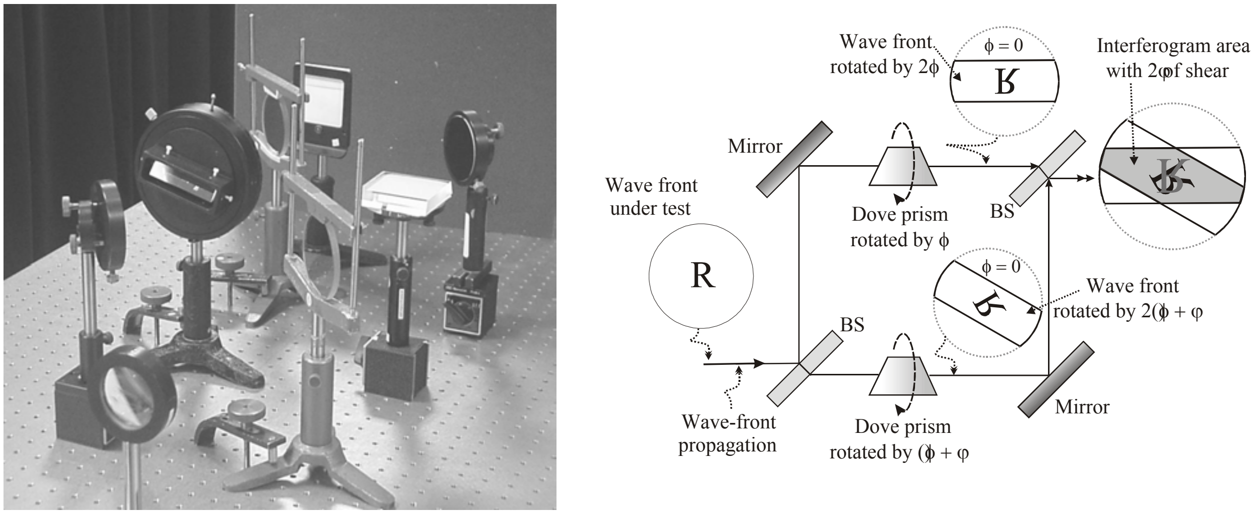

Fig. 2. A rotational shearing interferometer (RSI) implemented in a Mach-Zehnder configuration may be used to detect extra-solar planets or to test optical systems without rotational symmetry.

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