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**HOLOGRAPHIC LOCATION OF DISTANT POINTS
(PREPRINT)**

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14. ABSTRACT Imaging is the obvious way to find out about what a scene contains if we have little or no a priori information about what the scene contains. But that changes if we have a priori knowledge of things imaging would provide. There is inherent redundancy if we measure what we already know. For instance, if we know that the object is comprised of one or more isolated distant point sources, we need not form an image to locate those points. Imaging is costly in many respects and the nonimaging systems have significant advantages. This paper shows how to use holograms to construct a flat, solid, small, accurate, small nonimaging point location system.					
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Holographic Location of Distant Points

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Abstract

Imaging is the obvious way to find out about what a scene contains if we have little or no *a priori* information about what the scene contains. But that changes if we have *a priori* knowledge of things imaging would provide. There is inherent redundancy if we measure what we already know. For instance, if we know that the object is comprised of one or more isolated distant point sources, we need not form an image to locate those points. Imaging is costly in many respects and the nonimaging systems we have discussed earlier (1, 2) have significant advantages. This paper shows how to use holograms to construct a flat, solid, small, accurate, small nonimaging point location system.

Introduction

It is straightforward to view metrology in terms of communication theory. If the task is to measure the angular location of a single point, there are only two measurements required, in principle. More measurements can be used to obtain better accuracy. This suggests that the angular coordinates of the point be encrypted in some way so that the two or more measurements allow accurate decryption despite noisy measurements. Clearly, this fits within the much broader field of communication theory. Table 1 shows how to map the location of a single point onto communication theory. Multiple points are a simple extension.

	Communication Theory	Optical Metrology
Generality	Complete	A special case
Message	θ_x, θ_y	θ_x, θ_y
Encryption	Needs to be specialized to each case	The optical metrology physical setup
Receiver	Specialized to each case	Detector array
Description	Specialized to each case	Bayesian inversion

Table 1. The location of a point can be viewed in terms of communication theory. Our task is to choose a good physical measurement approach with a good encryption (the physical apparatus) and a good description (solution to the inverse problem)

Biomimetics and Bio Inspiration

Many animals have eyes and use them to locate things. We should be able to benefit from understanding what animals do to extract useful information from the light reaching their eyes. There are three aspects of natural vision that we use here.

First, there are animals that do not see an image. Frogs need to eat flies, crickets, and so forth. Their visual system sees only moving things of the right size to be prey (3). This is a good way to ignore noise and clutter while providing vital information, in principle. Specialized systems that simply supply the missing information that is needed to convert the generic description into useful information sometimes have value. Figure 1 shows how this parameter measurement method compares with image formation. If nature has been using nonimaging systems for hundreds of millions of years, there may be advantages worth exploring.

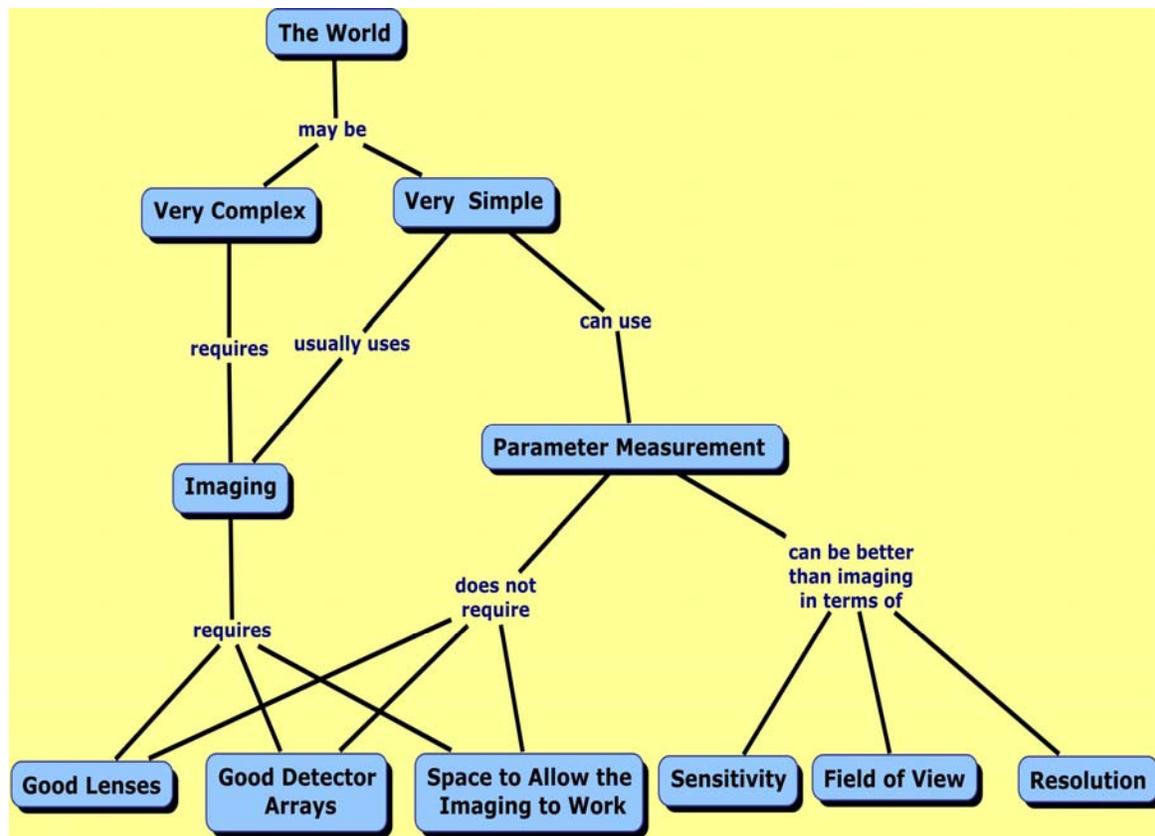


Figure 1. If we know little or nothing about the scene, imaging is a good way to find out what is there. If we know the form of the expression needed, we measure only to supply the missing information. Nonimaging systems may be superior in many ways. In particular imaging systems have characteristic drawbacks that nonimaging systems can be avoided altogether.

Second, nature may offer design concepts that are useful to us. This realization has become very widely useful in recent years. Systems that mimic at least some aspects of nature’s solution to some problems are said to be biomimetic. My first work in biomimetic point finding mimicked the multiple imaging systems that are comprised of independent narrow field of view units called ommatidia. Some ommatidia array form images and some do not. It is the latter that I emulated in what I will show here to be a rather poor approach. My student Luis Lopez made 100 ommatidia by hand and placed them on a 10 X 10 array with each facing a slightly different direction. We then moved a

point source to different angles and measured the 1000 signal levels. We then used a neural network to interpolate in 2D. The 10X10 array allowed position measurement of points within a 100X100 positions was encouraging (4). But the expense of such a system would likely be prohibitively expensive. This leads us to convert biomimetics to bio inspiration. Thos effective gain over direct imaging (that would produce precisely 10 X 10 pixels with a 10 X 10 detector array) can occur because each pixel position is encrypted by multiple ommatidia rather than just one. Qualitatively, this relates to the length of the code in communication theory. Communication theory also tells us that for any given channel there is a channel capacity relating to the signal to noise ratio such that there should be codes that transmit the information almost perfectly so long as the length of the encrypted signal divided by the length of the signal being transmitted exceeds that channel capacity. If the ommatidia have a fixed field of view, they can be arranged with differing degrees of overlap so that the total information is conserved. Small angular differences produce a small solid angle being measured but the measurements will be very accurate because the information is spread over many measurements. Likewise, of course, bigger solid angles can be probed at the cost of less location accuracy.

Third, strict biomimetics may not be the best way to achieve what nature does. The artificial ommatidia are a good example. It is easy to replace them with easier to make devices that accomplish the same sort of measurements. In terms of processing, it is often inappropriate to use biomimetics directly. Brains and computers have tremendous disparity in capabilities. Table 2 summarizes those disparities.

Properties	Computers	Brains
Major processor units	Transistors	Neurons
Speed of processing units	Very fast	Very slow
Number of processing units	Very large	Many orders of magnitude more
Primary processing strategy	Sequential	Parallel
Processing element complexity	Minimal	Huge

Table 2. Because brains and computers use such different processing elements, biomimetics should be avoided in favor of bioinspiration. We have to understand what the brain is doing and allow computers to accomplish the same tasks in ways that works for computers not brains.

Leonid Yaroslavsky and I and his students (1, 2) have explored some excellent inverse problem means for converting the encrypted locations of one or even several points. These are probably not the way nature would do it, so these are examples of bioinspired processing rather than biomimicked.

Advantages of this Method of Point Location

This approach is not the best way to measure point location by any linear means, as it is effectively a matched filter for collimated wavefronts. This repeats to some extent the advantages of this type of approach relative to imaging are summarized in Table 3.

Property	Imaging System	Nonimaging System
Diffraction limits	The best possible resolution	Irrelevant
Wavelength limitations	Very severe	Essentially none
Field of view	Somewhat limited	Up to 4π steradians
Impact of filter fields of view	Major problem	Easily accommodated
Lens design and quality and cost	Vital	irrelevant
Large volume for wavefront development	Inevitable	Irrelevant
Cost	Usually high	Can be small

Table 1. There are many advantages of using the bioinspired method described here relative to imaging

Basic Configurations

What we seek is a physical system that converts the angular directions of arrival into a code from which the two angular variables can be decoded. The angular sensitivity of a detector is governed by simple geometry. This is called the obliquity effect. So, different angles of arrival result in different signal levels. That means that every plane wave incident on the detection system produces its own unique signature pattern on the system. If we assume as well that the wavelength of the incident light is more or less monochromatic and that its wavelength is known. With those assumptions, a holographic method becomes quite attractive.

To place the holographic version in context, it will be helpful if the reader knows the other configurations we have considered.

There follows a list of nonimaging configurations we have studied or explored.

1. **Insect-eye models.** This was our initial version. We made and used artificial ommatidia each looking in a different direction. We then showed that a 10×10 array of ommatidia easily accomplished $10,000 \times 10,000$ location accuracy. But this was certainly not something that seemed to us to have little practical value. It did, however, inspire the rest of the work we have done. However, there has been recent work on making a cast of actual insect eyes and making ommatidia from them. This is of interest, because very small UAVs are being developed that might wish to use a point finder that can be mounted in such a system. Actual insect eye optics would be quite compatible with a small UAV. This approach would work well with gamma or x-rays, where the role of ommatidia could be played by thick metal collimators in the form of arrays of holes. The fields of view are governed by the aspect ratio of the holes. The incident rays are almost in axis so that grazing incidence should allow reflection.
2. **Detectors on curved surfaces.** It is not possible to tile a sphere uniformly with square detectors, so the preferred approach is to tile a cylinder with detectors.

That would measure one of the two angles of incidence and ignore the other. An orthogonal; cylinder could measure the orthogonal angle. Note that this makes it easy to cover 4π steradians. The radius of the sphere or cylinder allows tuning to high accuracy, as the detector's angular sensitivity pattern is probably hard to tune. A significant problem with this approach is that it does not appear to lend itself to low cost manufacturing.

- 3. Flat detector arrays with a positive lens more-or less in contact with it.** Rather than sample a flat plane wavefront with a cured array of detectors, why not convert the plane wave to a spherical or cylindrical wave and detect it with a flat array of detectors? Now the system is cheap to make. The lens converts the incident light from any distant point into a unique set of directions. The detectors will then convert that into a unique array of signal values that Bayesian inversion can convert into a measure of the source location. Normally, those rays are allowed to propagate to an image plane where they should all strike a single point. That requires that the various parts of the lens must be in the proper mutual phase relationship. That is why lenses are often hard and expensive to make. The implementation we propose is to detect the light long before it forms an image. That way, each detector senses the local ray direction through the obliquity effect and whatever other angle dependent effects there. An immediate benefit is compactness, but there are many others as we will show. The lens itself need not be very good, because there is no place where light from various parts of the lens must interfere accurately. Each part of the lens acts independently of the other.

Designing a Holographic Encryption for Point Location

Suppose we make a hologram array matched in size and pitch with the detector array. The holograms in that array are precisely aligned with the detector array to which they are aligned. The holograms need to be transmission holograms with each sending the incident light in its own direction. Ludman (5) had shown years ago that high efficiency and allowable angles of incidence can be achieved simultaneously.

Holograms can be made very small, but the question of importance for mass produced system is this: Can a detector array with large enough element spacing (pitch) to allow a significant number of a fringes within any facet. The good news is that the processing can learn to handle the actual signals that need not be ideal. It suffices to achieve two distinct requirements:

1. Repeatability and
2. Measurable differences between each element and its neighbors.

Fuzzy Metrology

Some time it is difficult to perform an act of classical metrology in which a physical event or structure must be compared with a standard. In such cases and in others as well, it may be useful to perform a kind of indirect metrology that I like to call Fuzzy Metrology (4, 6). In addition, we have now tested the Fuzzy Metrology concept in numerous ways. The basic idea is to measure to what extent the sought-after quantity is

present in certain predefined fuzzy sets. Those membership values can then be subjected to some kind of inverse solution: Figuring out what value the sought-after measurement must have to produce the observed set of measured membership values. But there are inevitable imperfections, unrepeatable noise, and so forth to complicate that inference. And we may have some information *a priori*.

Of course a wonderful method for this task (What fuzzy logic people call “defuzzification”) is given by Bayes’s Theorem. Ironically, devotees of Bayes’s Theorem and of Fuzzy Logic show genuine dislike to each other. But here is a situation in which both are extremely useful. For an introduction to Bayesian inversion and a hint at some of the philosophical aspects of it, see Dale (7). The point location method described here is an obvious case of Fuzzy Metrology. Some detectors receive more light than others, and in so doing create a unique set of measurements. Bayes’s Theorem provides an excellent tool for finding out the probability of all possible sets of θ_x , θ_y pairs. The most common approach thereafter is to declare θ_x , θ_y to be the pair that is most probable: The Maximum A Posteriori or MAP values. This is a very reliable estimation, as its few assumptions (the priors) are explicit and easily changed.

In Refs. 1 and 2, my colleague Leonid Yaroslavsky used a related approach called Maximum Likelihood or ML theory – a kind of statistically regularized curve fitting that injects more assumption and sometimes gets a better estimate in so doing. Readers interested in ML may wish to see the excellent online tutorial by Purcell (8). Many plots of point location accuracy for multiple points with various amounts of noise are given and discussed.

Cheeseman and Stutz (9) have made a detailed comparison of the relationship between Bayesian inversion and Maximum Likelihood fitting (9). Among their conclusions is: “We find that these differences are due to the Bayesian inference not assuming anything beyond the given prior probabilities and the data, whereas MaxEnt implicitly makes strong independence assumptions, and assumes that the given constraints are the only ones operating.”

Thus there are at least two distinct and well studied approaches to the defuzzification of the set of membership values measured. At this moment, it seems to me premature to declare a winner for all cases.

Figure 2 shows a Concept Map of what Fuzzy Metrology does and its relationship to conventional Crisp Metrology.

Conclusions

Finding the directions of arrival of collimate beams of light is important in some situations. When it is appropriate, it is fairly easy to make suitable nonimaging systems that encrypt the directions of arrival in such a way as to allow the inverse solution to be solved to reveal the angles. Using a hologram array mated to a detector array is all that is needed to do this. The resulting system is very inexpensive and small and is not

resolution-limited in accuracy by diffraction. The use of a hologram array makes the design very flexible. Diffractive optics (a kind of hologram) is computer designed and can be replicated easily.

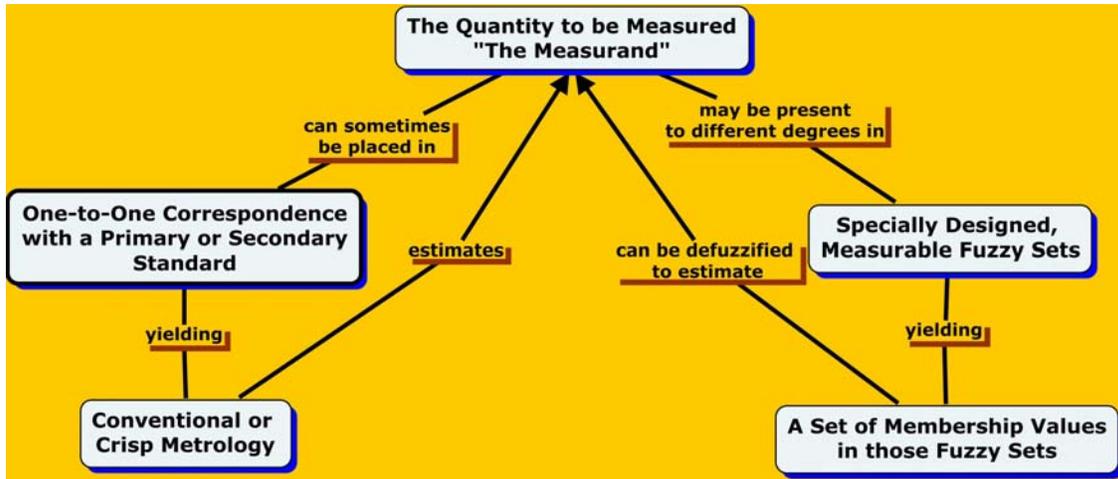


Fig. 2. There are two distinct ways to measure something. The conventional, “crisp”^{*} way seeks to produce a situation such that the thing to be measured is directly compared to a standard. Fuzzy Metrology, on the other hand, measures the extent to which the thing to be measured can be considered as a member of certain predefined fuzzy sets. To get the desired numerical value, some sort of defuzzification is needed. The differences between those two approaches are discussed here and in more detail in References 4 and 6.

References

1. [H.J. Caulfield](#), [L. P. Yaroslavsky](#), [Ch. Goerzen](#), [S. Umansky](#) “Optics-less Sensors for Localization of Radiation Sources,” [arXiv:0808.1259](#) [pdf, other]
Title: Computational Vision in Nature and Technology
2. [Leonid Yaroslavsky](#), [H. John Caulfield](#) , “Computational Vision in Nature and Technology,” [arXiv:physics/0703096](#) [pdf]
3. J. Y. Lettvin, H. R. Maturana, W. S. McCulloch, and W. H. Pitts, “What the Frog's Eye Tells the Frog's Brain,” Proc. IRE 47, 1940-1951 (1959)
4. H. John Caulfield “Fuzzy Optical Metrology,” IEEE Transactions on Fuzzy Systems 4, 206-207 (1996)
5. J. R. Riccobono and J. E. Ludman, “Method of manufacturing high efficiency, broad bandwidth, volume holographic elements and solar concentrators for use therewith,” United States Patent 5517339 (1996)
6. H. John Caulfield, Jacques Ludman and Joseph Shamir **Fuzzy Systems Theory Vol. 2**, Academic Press, NY 26 “Fuzzy Metrology” Pages 747 – 758 (1999)

^{*} Fuzzy logic practitioners use “crisp” to mean the conventional, well-defined value as opposed to a fuzzy value. In the end, after doing computations in the fuzzy domain, they often have to produce a crisp value. That process is called “defuzzification.” Creating a fuzzy set from crisp values is called “fuzzification.”

7. Andrew I. Dale, **A History of Inverse Probability: From Thomas Bayes to Karl Pearson**, Springer-Verlag, 1991
8. S. Purcell, “Maximum Likelihood Estimation”
http://statgen.iop.kcl.ac.uk/bgim/mle/sslike_1.html last update 2007
9. P. Cheeseman and J. Stutz, “On the Relationship between Bayesian and Maximum Entropy Inference” in Bayesian **Inference and Maximum Entropy Methods in Science and Engineering: 24th International Workshop on Bayesian Inference and Maximum Entropy Methods in Science and Engineering**. AIP Conference Proceedings, Volume 735, pp. 445-461 (2004). This paper is also available online at
[http://ti.arc.nasa.gov/m/pub/807h/0807%20\(Cheeseman\).pdf](http://ti.arc.nasa.gov/m/pub/807h/0807%20(Cheeseman).pdf)

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