Discover better Optical Sensors - by Exploring and Exploiting Nature's Limits

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Abstract: Nature's limits are precious: they often reveal uncertainty products connecting coherence, resolution, precision, channel capacity… So we can bargain with nature for "optimal" 3D sensors with novel features or just better precision, resolution, speed.
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1. About important problems, and how much optics or computing to solve them

This is a retrospective insight the author wishes someone would have given to him as a young student. It is as well an essay to organize results of some 40+ years of research into a two-page generic framework.
According to Einstein (cited from [1]), the most noble mission of a scientist is to pose important questions - the remaining part just engineering and mathematics. But how to find important questions? For a young opticist, a good source might be industry calling for the solution of a difficult metrology problem. If the problem has not yet been solved by competing clever scientists, it might be a really important one. The problems of optical metrology and imaging are about lateral- and longitudinal- or angular resolution, localization, precision (noise!), accuracy, measuring range and field of view. And of course about measuring speed (never enough) and cost (always too much) – the latter problems being highly connected with information concepts. But even without the kick from industry, the strategy of searching for nature's limits makes a scientist rich. The strategy obeys Einstein's imperative and satisfies our curiosity. And the findings might be precious for better sensors or even for sensors with novel, yet unknown features. The strategy will be illustrated by a few results of our group at Erlangen. The author's viewpoint is that of a physicist and engineer: computational optics with as much optics as necessary (to avoid the garbage-in / garbage-out problem), and as much computing as possible (for flexibility and low cost).

2. Precious limits

Knowledge about nature's limits is precious: we can save money, as hitting limits makes further technology investments riding a dead horse. We know as well if our competitor's datasheet is lying or if his instrument displays room for improvement. The major incentive however is, limits come as (uncertainty) products [2]. Which means we can bargain with nature (notice: she will never give presents). The most fundamental limit is the Heisenberg limit. Bothering Heisenberg appears to be overkill, but in fact many daily life limits follow from this relation, such as Abbe's resolution limit δx and the Rayleigh depth of field δz_R. Combining Abbe and Rayleigh we get $\delta x^2/\delta z_R=\lambda$. As a warm up question: does this mean that the lateral resolution and the depth of field (dof) are inseparably coupled? No, there is no hard limit for a large dof with at the same time high lateral resolution [3]. But nature asks for compensation: the incoherent point spread function psf(r) (r=distance from center), after dof-expansion, is not anymore dropping with $1/r^2$ but only with 1/r, with serious consequences for the image contrast. Its origin is the same as the 1/r drop of the psf in X-ray tomography and cannot be overcome by linear optics.

Optical limits originate from diffraction and from noise. So the dominant source of noise is crucial. It may be photon noise, but practically for all daily life optics and specifically for triangulation (including stereo vision, confocal microscopy …) the dominant noise originates from spatial coherence. Depressingly, (partial) spatial coherence is ubiquitous [4,5]. Modern microscopy overcomes coherent noise by exploiting fluorescence ("F-techniques"), and other classical limits by involving nonlinear optics and quantum methods (STED microscopy…). For technical metrology we found that all (?) 3D-sensors are based on only four signal generating mechanisms which differ by the kind of noise and how the noise afflicts the precision. Here the compressed facts:

3. Limits: Triangulation, 'Coherence Radar', Deflectometry, Classical Interferometry

Triangulation: The most common sensors (for rough surface metrology) are based on triangulation, among these are, confocal microscopy, 'fringe projection', laser triangulation. The depth precision of these systems is $\delta z=C\lambda/(2\pi \sin^2 u)$ [4], where *C* is the coherent noise contrast, and *sin u* the observation aperture. For lasers *C=1*. But even for sunlight or other spatially and temporally incoherent sources, coherence theory tells us that *C* might not become much smaller than 0.1, depending on the ratio of illumination aperture vs observation aperture [5]. The large illumination etendue required for low noise introduces another deep limit, strongly connected with information aspects [6]. The unavoidable coherent noise is devastating for triangulation and indeed it was the trigger to look for *rough surface metrology* that is not dominated by coherent noise. We called the new method „coherence radar":

White light interferometry on rough surfaces [7], exploits spatial coherence (speckle) and temporal incoherence. The depth precision δz displays a very strange behavior: $\delta z \approx \sigma_o$ where σ_o is the surface roughness of the sample. Please note, the precision δz does not depend on the observation aperture, so we can measure within deep boreholes. We can even measure the surface roughness from a remote distance, without resolving the surface micro-topography [5]. In other words, nature permits us a peek into the realm „beyond Abbe". The coherence radar offers some more surprising and useful features: in the conventional embodiment one interferometer mirror is replaced by the (rough) object. But we can replace the other mirror as well, creating an interferometer with two rough „mirrors". This modification does not anymore require a telecentric system and can measure very large objects. We should emphasize the option to measure volume scatterers such as skin (Time Domain OCT) and the Fourier domain modification of the coherence radar (FDOCT) [8,9].

Deflectometry [10], measures specular surfaces by evaluating the reflection of a known pattern at the surface under test. It displays a really precious uncertainty product: $\delta x\ \delta\alpha = \lambda/SNR$, $\delta\alpha$ being the angular precision. The dominant source of noise now is photon noise, with a nice consequence: As it is easy to measure with many photons, there is virtually no limit for the angular precision, even more so if we sacrifice some lateral resolution δx. Already with SNR≈500 we achieve a depth precision $\delta z = \delta x\ \delta\alpha \approx 1\ nm$. It is not only shot noise domination that makes deflectometry so powerful. Deflectometry is a paradigm example of „*optical pre-processing*", or in terms of information theory „*source- (or channel-) encoding*": the object redundancy is largely removed by a priori optical differentiation *grad z(x,y)*. Information theory tells us that source encoding has to be done before the noise is added in the channel. This makes *optical processing* a necessary condition ("in the beginning … there was light!").

Classical interferometry is shot noise dominated as well, so there is virtually no lower limit of δz (which enables gravitational wave interferometry with $\delta z < 10^{-20} m$). It might be interesting, that in contrast to the coherence radar, classical interferometry displays lateral averaging over the surface micro topography (for surface roughness $\sigma_o << \lambda$). So classical interferometry displays aperture dependence.

4. Speed and Channel capacity

One more limit, coming into play via information theory, is the channel capacity *CC [bit/sec] ≈ SBP log (SNR)*, with *SBP* the space (time)-bandwidth product (≈ number of transmitted 3D-pixels per second) and *SNR* the dynamic range of our sensor (depth range / depth precision). Providing a sensor with large *CC* is expensive. So we must take care via proper *optical encoding* that the sensor input information does not require a big *CC* [11]. A well designed sensor should have a high information efficiency η *= output information / CC.* Most optical 3D-sensors display intrinsically a low efficiency, as a single 2D image does not deliver sufficient information for full field dense 3D data. But there is still much room for improvement. Examples for this kind of reasoning are given in [12,13].

5. References

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