A POSSIBLE SCENARIO FOR VOLUMETRIC DISPLAY THROUGH NANOPARTICLE SUSPENSIONS

Enrique Canessa

The Abdus Salam International Centre for Theoretical Physics
Trieste, Italy

Abstract

We discuss on the potential of suspensions of gold nanoparticles with variable refractive index for the possible physical realization of *in–relief* virtual dynamic display of plane images. A reasoning approach for a vision system to display in real–time volumetric moving images is proposed based on well–known properties of optical media, namely the anomalous dispersion of light on certain transparent media and the virtual image formed by a refracting transparent surface. The system relies on creating mechanisms to modify the refractive index of *in–relief* virtual dynamical display (iVDD) bulbs that ideally would contain a suspension of gold nanoparticles each and that might be ordered in an array filling up a whole screen.

In this work we present an approach for a vision system based on suspensions of gold nanoparticles with variable refractive index that could allow to depict in real–time and *in–relief* two–dimensional 2D (*i.e.*, planar or flat) virtual images such as light rays that do not converge to the image point but appear to emanate from that point that could be in movement.

To perceive, recognize and gauge with our brain the *depth* of a 3D picture, nature provides us with two images of the same scene (the so–called *stereopsis* process [1, 2, 3, 4]). The amount of depth perceived also depends on the binocular disparity between the two eye views. The wider the separation, the greater the apparent depth is. By moving our head and looking around objects, we change our view and judge depths of objects at different distances from our eyes (the *parallax* phenomenon). The brain also uses the so–called *accommodation* of blurred images to gauge depth from the muscular contraction of the *lens* surface of the eyes.

Besides the input signals from the two eyes, the brain also uses other cues in the determination of depth. These include the cues that artists rely on to convey a feeling of depth in 2D paintings. Artists convey the roundedness of an object by varying color or indicating the different light intensities on different surfaces (*e.g.*, shadows). Flat, static pictures can also take on some depth by variations in the sharpness of distant objects (*e.g.*, perspective) or by the interposition (*i.e.*, occlusion) of objects.

Separate images to each eye can also present a binocular disparity and hence a 3D view to the observer (*e.g.*, as seen by binoculars). To this end, the stereoscope presents two different pictures to each eye whose viewing appears in depth due to their differences. This old–technique has been used, *e.g.*, in Astronomy to notice changes in the stars positions. Other attempts for achieving static 3D displays are in–relief posters and maps, multiple–layer postal cards, etching monographs, embossed image art, sculptures, holograms (to record and store 3D visual information to be re–displayed under proper illumination), *etc.*

The shape–from–shading (also known as *photoclinometry*) is a method used to view planar images in 3D by mathematically relating image intensities and brightness [5]. Other mathematical techniques make it also possible to reconstruct from 2D projections and get a full 3D picture [6].

Alternative techniques to visually fathom the depths of the world in movement around us have been also explored. These include the 3D–like Cinevision with added external effects and objects (*e.g.*, perfume, dummies and quakes superimposed), the virtual reality (with simulated virtual touch) and 3D computer vision [7] (based on perspective and light intensity changes and motion sensors). Related work on the 3D display using non–linear optics can be found in [8].

Motivated by all this firestorm of ongoing activity on the search of techniques for giving the impression of reality (depth) and hopes for subsequent realistic displays, we focus next in the possible vision system based on suspensions of gold nanoparticles with variable refractive index. To achieve an enhanced depth by the *in–relief* virtual dynamical display (iVDD) of plane images, it is necessary to consider first two physical phenomena as seen in nature and described by geometrical optics (apparent depth) and nonlinear optics (anomalous refraction index).

Images of objects inmersed in a medium with refraction index n_1 are formed by the refraction of rays at a, say, spherical surface with radius R of a transparent material with a different n_2 [2]. By applying Snell's law to the refracted rays and after a simple geometrical construction, it can be shown that $\frac{n_1}{p} + \frac{n_2}{q} = \frac{n_2 - n_1}{R}$, where p is object distance and q is image distance from the spherical surface. For a flat surface, one approximates R to infinite hence for small angles

$$q \approx -(n_2/n_1)p \quad . \tag{1}$$

When the sign of q is opposite to that of p, the location of the virtual image is on the same side of the surface as the object.

It is well–kwown that the refractive index (or index of refraction), characteristic of a substance, varies with light. If n changes we then deduce from Eq.(1) that the position of a virtual image might move as a function of the frequency of radiation λ. The nonlinearity of the refractive index versus λ in certain optical media as well as the connection between *dispersion* and *absorption* has been known for many years [9]. (For details of the treatment of dispersion according to quantum theory and classical Lorentz electron theory see, *e.g.*, [4, 10, 11, 12, 13].

Absorption involves the excitation by radiation of an electron from its lowest energy state to a higher energy state by the incident light wave (quantum confinement). Usually not all of the absorbed energy is re–radiated, remaining as heat in the absorbing material. In quantum theory, absorption is associated with transitions between quantized energy levels. Whereas according to classical theory, this phenomenon is identified with the steady oscillation of a charge in an orbit reacting to radiation. Each electron oscillator has a resonance frequency and, near resonance, the damping oscillator produces the broadening of the amplitude response.

The refraction or bending of a ray of light that passes through a medium is the result of the diminished transmission rate of the wavefronts in the medium. The velocity of light propagation in the medium varies considerably with wavelength ω hence the refractive index n varies with the wavelength of the incident light. When ω approaches the wavelengths of strong absorption bands of the medium, n undergoes sharp changes around resonant frequencies λ_R.

This anomalous behavior of n was first observed in electrically excited rarified gases some time ago (see reviews in [14, 15]). Since then, there has been a continuing interest in investigating the exceptionally high values of the refractive index near resonance lines by laser excitation in bulk semiconductors [16, 17] and Sodium vapor [18] to mention a few. Experiments in air and diatomic gases show that the resonant wavelengths lie in the ultraviolet (*i.e.*, shorter than the visible wavelengths). The characteristic damping times for the resonances are usually compared with the incident light intensity pulses used.

Variations in density ρ (due to, *e.g.*, compressibility) [13], in small temperature gradients [19] and in angle of light incidence [20] also produce changes in optical refractivity. Though such changes are not sufficient to produce appreciable percentage of excited states (and produce the so–called *'negative dispersion'* effect).

Within classical electromagnetic theory, n is represented as a complex, frequency dependent quantity [10, 13]. It can be shown that $n(\omega) = Re\sqrt{\epsilon(\omega)}$, where ϵ is the dielectric permittivity of the medium, and the absorption coefficient is given by $\delta(\omega) = -2(\omega/c)Im\sqrt{\epsilon(\omega)}$.

There is also a close relation between dispersion and absorption. For a Lorentzian oscillator, the extreme values of n occur at a frequency at which δ has half its maximum value and it can be approximated by [13]

$$(n-1)_{extreme} \approx n_o - 1 \pm \frac{\delta_{max}}{2} \quad , \tag{2}$$

where $n_o - 1$ is the reduced refractivity due to different electron oscillators per molecule.

It is important to mention that measurements of nonlinear refraction at room temperature and upon (~picosecond) excitations by a laser pulse have also been reported in porous–glass nanocomposite materials [21, 22] and transparent dielectrics materials [23] owing to their potential applications for improving the performance of photonic devices. On the theoretical side, the electronic properties of these particles with diameters of few up to ten nanometers and embedded in a dielectric have been studied in [24, 25].

A large amount of work has also been devoted to the study of quantum size effects in suspensions of submicron size colloidal particles [25]. However, it has been only in recent years that the ultrafast nonlinear response of metal colloids to light has been measured (whose diameters are much smaller than the optical wavelength) [26, 27, 28]. These fascinating nanoparticle systems, which are neither quite microscopic nor quite macroscopic [25], are of our interest for the iVDD implementation and the possible 3D display of visible plane surfaces.

Experimental results using a single beam technique [29], show that the non–linearity is *ultra–fast* with response time shorter than, *e.g.*, the 28 *ps* pulse duration of the laser used. The absorption spectrum of gold nanoparticles having mean diameter of ≈ 20 *nm* displays a maximum at a frequency of ≈ 525 *nm*. Particles larger in size have a red–shifted plasmon maximum [30]. Copper nanoparticles in 2–ethoxyethanol and water shows distinct absorbtion peaks at 572 and 582 nm, respectively [31].

The optical response of rod–shaped gold nanoparticles in solutions, with different aspect ratios, is also of interest in the visible [32]. It has been observed that their absorption spectral features consist of a dominant surface plasma attributed to the collective dipole oscillation corresponding to the longitudinal resonance.

Its characteristic frequency shifts to the red when increasing the anisotropic shape of the nanorods. As with the nanoparticles in suspension, data from human photoreceptors in the retina shows that the wavelength of maximum absorbance of the sensitive receptor cells known as cones lies also in the range $534 - 564$ nm [33].

As anticipated, the initial stages of image processing in nature consist of fairly simple, usually local, transformations of the array of (refracted light) intensity values in the image [1]. Inspired by these observations, in what follows, we introduce the iVDD system for the image filter that might produce the sensation of depth under normal viewing conditions without the use of external glasses or special sensors.

An input signal (such as a TV signal comming from an antenna) could be simultaneously displayed in two receiver sets. A radiation–sensitive detector photodiode that converts light into an electrical signal, placed in front of one of the TV screens, could be used for the voltage analysis of the time–varying imagery in real time. The photodiode could send a voltage signal to a selective switch. The switch could possess two different (or a discrete set of) output states of emitted light that could radiate the iVDD bulb in the visible portion of the electromagnetic spectrum in which the moving images containing 2D information transmitted by a second receiver set might cross.

Following reported experimental data, if frequencies at or near resonance λ_R can be used to radiate the iVDD bulb, sufficient excitation of energy states would produce a nonlinear n of the suspension. Since the refractive index of the iVDD bulb (filled with the nanoparticles) would change abruptly then one can deduce from Eq.(1) that the position of a virtual image should move (back or forward) as a function of the frequency (greater or smaller than λ_R). The incident wavelengths should be near (and not equal to) the wavelength at which the nano gold colloidal suspension has a *maximum* absorption. So little should be transmitted or reflected of the incident light in a similar way to fluorescent–tube discharge lamps where the incident UV light excites a fluorescent coating on the internal surface of a bulb.

A coherent laser light could be activated by the voltage signals coming from the photodiode. The required high–frequency radiation could be produced by, *e.g.*, a Nd:YAG laser ($\lambda \approx 530\ nm$) providing 30 ps pulses at a repetition rate of 10 Hz [26]. (For visible light, one requires frequencies of the order of $3\ 10^6 GHz$: since $\lambda = c/\omega \approx 3\ 10^8/100\ 10^{-9}$ cycles per seconds. The use of incandescent and fluorescent lights might also emit light in this frequency range. Besides, acoustic–optic modulation might alter the refractive index as observed in recent experiments in optical fibers [34, 35].

Because the refractivity should vary sharply over the profile of a spectral line due to the smallness of the particles inside the iVDD bulb, the propagation of the two wavelengths of light through the iVDD bulb will cause the position of a virtual image formed in the iVDD bulb to move as a function of the frequency of radiation according to refraction phenomena. This effect would allow to simulate spatial information out of the planar images. By using reported experimental data for the absorbance spectra of gold particles in suspension, we carry out a crude estimation for the extreme value of n given in Eq.(2) and found that the virtual image would have (maximum, minimum) depths of about ±15% from the receiver screen distance.

Thus, our simple system involves the generation of light excitation as emitted, *e.g.* from a TV screen. This radiation could be used to alter the refractive index of a stable inhomogeneous nanoparticle dispersion which generates an *in–relief* virtual dynamical viewpoint and allows to gain depth control by the light–frequency filtering. Due to the fast–response time of the non–linear dispersion, motion changes should appear as in TV and cinema motion which consists of a permanent stream of frame pictures. The electron beam fired out of a gun inside a TV set hits a phosphor–coated screen to draw a picture at a rate of 30 times every second.

In principle to transfer the full screen information one could think of an array of iVDD bulbs filling up the screen area. Each screen pixel to be seen *in–relief* should be in correspondence (and be representable) with the 2D full screen. The viewer would see a virtual image which might appear as a relief image of the original full–screen object.

The present system needs to be compatible with TV broadcast standards and standard home TV receivers, including the new digital TV broadcasting which allows to improve the overall quality of the picture (overcoming the problems of ghosting and compressing the signal) [36, 37]. If we consider a (black and white) rectangular computer screen (roughly $25cm$ diagonal) having an array of 640 by 480 pixels, then one would need about 307,200 iVDD bulbs to cover out all the screen.

Of course, the present ideas are only speculation as there are many technical problems to consider in practice. A few of these are discussed next for completeness.

To the best of the Author's knowledge there does not exist a similar proposal for a possible iVDD system described in the literature (combining both nonlinear optics phenomena and simple laws of geometrics optics as used here), or a similar product available in the market, or a similar claim in the USA patents database [38].

Although certain significant properties of optical media have long been studied by specialists, the techniques and instruments which could make them observable (*e.g.*, precision and sensitivity of measurements) have been only available in recent years. These include small, high–tech lasers (with low power requirements, low phase noise and superior frequency stability). The high light frequencies needed for the iVDD system are not yet achieved by commercial *Voltage Controlled Oscillators* (VCOs) which are widely used for wireless communications. These are available in radio frequencies spanning 100 MHz to 3 GHz with supply voltages ranging from 3 to 12 Volts and operative over a wide range of temperatures. Tiny Crystal Clock Oscillators allowing fast delivery of many frequencies are only available in this range. All this technology is developing.

Put more precisely, it is only now possible that these thoughts for a 3D virtual dynamic image could become feasible. To have a suitable experimental test platform, the system relies on creating reliable mechanisms to modify the iVDD bulbs's refractive index displaying the recent observed non–linear optics properties of small metal particles in suspensions which could be ordered in an array to fill up a whole screen.

In theory the present vision system for displaying in real–time and *in–relief* 2D moving images should overcome the following problems: One should search for the best transparent material for the iVDD bulb container of the nanoparticles in suspensions (made of lens; glass bounded by smooth "curved" surfaces). One should identify which thin optical elements to use to reduce aberration (if any will appear). It would be necessary to control the size distribution as well as the stability of the gold nanoparticles in suspension against agglomeration (percolation) and sedimentation. It is well–known that grafted polymers represent an interesting alternative means to obtain a solid matrix and control interparticle separation. Gold–graft copolymer composites could then be used to characterize the distribution and spatial arrangement of the nanoparticles. One should avoid using *photorefractive* materials – the subclass of nonlinear optics materials in which light emerging from such substances does not necessary have its frequency proportional to the incoming light. It is necessary to investigate the characteristic frequencies (leading to transition on the visible) of the optical transparent media to be used. One should identify the optimal visual angle and the possible range of vision. The iVDD should be isolated from vibration. Small vibrational disturbances on the iVDD bulbs might cause the outgoing laser transmission beam to deviate from the desired pointing angle. One should quantify the iVDD (fast) response times to control and avoid superimposition of images. One should avoid to have images magnified upright (M=*image height/object height*). One should avoid double refraction (through birefringent substrates) in optically anisotropic media. One should identify if there is any absorbed energy not re–radiated, remaining as heat in the absorbing material.

To conclude we would like also to mention that laser–induced holographics TV, (*i.e.*, moving holographic videos with a wide–angle display of 3D dynamic images) is being developed by the

MIT's Media Laboratory whose usage is expected by the year 2020 [39]. Our iVDD system could differ from Holographics TV by the following. In principle, the iVDD system could display "mezzo" relievo images only and not a full volumetric, 3D display as in holographics TV. It could display in–relievo images over a reduced angle–range vision –holographic video display is capable of rendering full–color 25x25x25mm images with a 15^o view–zone at rates over 20 frames per second. The iVDD system could contain less information than holograms and could also require a Laser source. However, it might require simpler manipulation as it could be easy to attach to present TV or Computer screens.

In order to get visual effects that might look like the real things one could try the iVDD. It could be a reasonable, cost–effective alternative to holographic TV because the costs of large optics necessary for holographics TV could be reduced to acceptable levels. Our iVDD system could also be compatible with display media other than TV, *e.g.*, *in–relief* Computer and, probably, Cinema screens. Many practical applications can be anticipated including the entertainment and cultural business. The iVDD system could help to medical imaging in real time, robotics, design, *etc* as well as to preserve realistic vision of extincted species and/or rare objects of which only photographic records exit.

It has been said that *virtual images cannot be displayed on a screen* (see, e.g., Ref. [2]). However, a reasonable approach indicates that there could be a way for achieving this optical phenomenon on a large screen made of an array of tiny Virtual Dynamical Display (iVDD) bulbs containing gold nanoparticle suspensions. One could also think of the two different input images to be displayed in two separated planes and that the resulting image disparity would be sufficient to create a steroscopic view to cross the iVDD bulbs.

References

1. O.J. Braddick and A.C. Sleigh Editors, in Springer Series in

Information Sciences, Vol 11, *Physical and Biological Processing of Images*, Springer–Verlang, Berlin, (1983).

2. R.A. Serway, in *Physics for Scientists & Engineers*, Saunders College Publishing, 1996.

3. D.S. Falk, D.R. Brill and D.G. Stork, in *Seeing the Light: Optics in Nature, Photography, Color, Vision, and Holography*, Harper & Row Publishers, New York, Chapter 8, 1986.

4. M. Born and E. Wolf, in *Principles of Optics*, Pergamon Press, Oxford, 1975.

5. B.K.P. Horn, Artificial Intelligence, **8**, 201 (1977).

6. R. Gordon, G.T. Herman and S.A. Johnson, Sci. Am. **233**, 56 (1975).

7. E.A. Bretz, IEEE Spectrum, page 42, January 1998.

8. E.A. Downing, L. Hesselink, R.M. MacFarlane, *A Solid–State Three–Dimensional Volumetric Display*, Conference Proceedings of the Lasers and Electro–Optics Society, Annual Meeting, **8**, 6 (1994).

9. See, *e.g.*, *Encyclopedia of Physics*, S.P. Parker Ed., Mc–Graw Hill Book Company, Ney York, page 12, (1988).

10. S.A. Akhmanov and S.Yu. Nikitin, in *Physics Optics*, Clarendon Press, Oxford, 1997.

11. G.C. Baldwin, in *An Introduction to Nonlinear Optics*, Plenum Press, New York, 1969.

12. F. Zernike and J.E. Midwinter, in *Applied Nonlinear Optics*, John Wiley & Sons, New York, 1973.

13. D. Bershader, in *Modern Optics Methods in Gas Dynamic Research*, Ed. D.S. Dosanjh, Plenum Press, New–York, page 65, 1971.

14. S.A. Korff and G. Breit, Rev. Mod. Phys **4**, 41 (1933).

15. R. Landenburg, Rev. Mod. Phys. **5**, 243 (1933).

16. N. Peyghambarian and S.W. Koch, in Springer Series in Electronics and Photonics, Vol 30, *Nonlinear Photonics*, H.M. Gibbs, G. Khitrova and N. Peyghambarian Eds., Springer–Verlang, (1990).

17. D. Ricard, P. Roussignol, F. Hache and Ch. Flytzanis, phys. stat. sol **159**, 275 (1990).

18. E. Kügler and D. Bershader, Exp. Fluids **1**, 51 (1983).

19. H. Fiedler, K. Nottmeyer, P.P. Wegener and S. Raghu, Exp. Fluids **3**, 145 (1985)

20. D.K. Lynch and W. Livingston, in *Color and Light in Nature*, Cambridge Univ. Press, 1995.

21. R.J. Gehr, G.L. Fisher and R.W. Boyd, J. Opt. Soc. Am. B **14**, 2310 (1997).

22. K. Uchida *et al.*, J. Opt. Soc. Am. B **11**, 1236 (1994).

23. M. Sheik–Bahae *et al.*, IEEE J. Quantum Electron. **26**, 760 (1990).

24. F. Starrost *et al.*, Phys. Rev. Lett. **80**, 3316 (1998).

25. J.A.A.J. Perenboom, P. Wyder and F. Meier, Phys. Rep. **78**, 173 (1981).

26. M.J. Bloemer, J.W. Haus and P.R. Ashley, J. Opt. Soc. Am. B **7**, 790 (1990).

27. A.W. Olsen and Z.H. Kafafi, J. Am. Chem. Soc. **113**, 7758 (1998).

28. S.C. Mehendale, S.R. Mishra, M. Laghate, T.S. Dhami and K.C. Rustagi, Opt. Comm. **133**, 273 (1997).

29. M. Sheik–Bahae *et al.*, IEEE J. Quantum Elec. **26**, 760 (1990).

30. T.S. Ahmadi, S.L. Logunov and M. A. El–Sayed, J. Phys. Chem. **100**, 8053 (1996).

31. H.H. Huang *et al.*, Langmuir **13**, 172 (1997).

32. Y.–Y. Yu, S.–S. Chang, C.–L. Lee and C.R.C. Wang, J. Phys. Chem **101**, 6661 (1997).

33. J.K. Bowmaker and H.J.A. Dartnall, J. Physiology **298**, 501 (1980).

34. T. Kato, Y. Suetsugu and M. Nishimura, Opt. Lett. **20**, 2279 (1995).

35. P.D. Townsend, A.J. Poustie, P.J. Hardman and K.J. Blow, Opt. Lett. **21**, 334 (1996).

36. J. Moroney, Global Commun. Interactive'97 Edition, p91.

37. U. Reimers, Phys. World, p.39, April 1996.

38. An extensive on–line search was carried out by the author using the IBM webserver at http://www.patents.ibm.com To mention the most relevant, a method and an apparatus: (i) for creating an illusion of depth when viewing through special eyeglasses moving pictures projected in a plane surface has the US Patent number 5434613; (ii) for producing a stereoscopic TV image giving the illusion of 3D depth has the US Patent number 4567513 (further references are given therein). 3D display has also been achieved using special projectors (see, *e.g.*, US Patent numbers and titles: 3674921–Three dimensional television system, 5448287–Spatial video display system, 566831–Three dimensional display, 5714997–Virtual reality television system and 529323–Apparatus and method for producing 3D–dimensional images).

39. S. Bains, New Scientist, Vol.155, page 28, July 1997.