Physics – Uspekhi **37** (9) 889 – 899 (1994)

INSTRUMENTS AND METHODS OF INVESTIGATION

PACS numbers: 07.05.–t, 42.30.–d, 42.66.Si

Computer generated three-dimensional representations of objects

A A Vedenov

Contents

Abstract. Today scientists can create, with the aid of a personal computer three-dimensional (3D) representations of objects — a specific data base, containing not only the space coordinates and colours of all points of an object, but also allowing it to be examined from a bird's-eye point of view. The data base reveals the characteristic features of the object as a whole and allows them to be named. Examples of 3D representations are given and the principles of their creation and viewing are discussed.

"Frankly speaking, I don't like to listen to news reports on the radio... My globe is much more convenient... If you look closely, you will see the details as well ..."

Margarita bent over the globe and the square of land expanded, became infused with many colours and turned into something like a relief map.

Mikhail Bulgakov *The Master and Margarita*

1. Introduction

With the aid of a personal computer it is now possible to create three-dimensional (3D) representations (copies) of objects. Such copies can then be inspected from different points of view and different distances with the help of any of the known methods of individual and collective viewing of stereo images, as well as by means of standard modern methods of 3D visualisation.

To construct a 3D computer copy one can use the results of various physical measurements or photographs of the object.

A personal computer allows the expert to use his deep knowledge of 3D objects in his area of research (the mental representation of the object, which is extremely difficult to formalise) for interpreting the results of measurements or for reconstructing the usual flat 'copy' of an object — its photographic image (optical, electronic, x-ray, infrared). The 2D image is in essence a greatly distorted copy, compressed in one direction — in depth, and its reconstruction results in the creation of a true 3D image of an object.

The 3D object can be a set of points, lines, or surfaces in space; lines and surfaces themselves also consist of points. The points are coloured; in modern personal computers the colour of a point is characterised by the intensity of red, green, and blue colours (RGB), which for each of the colours can take on an integer number from 0 to 255.

After a 3D object has been created in the computer, the question arises how to examine it.

No doubt 'glass-like' media (such as aerogel or other transparent substances) will soon become available for the visualisation of 3D models, with the possibility to address any given point of the volume and insert at this point a colour with a unique value of the RGB palette. But flat image carriers (paper, photographic film, flat screen) will remain the most commonly used media and in many cases the most convenient ones.

In some cases for the adequate perception of volume it is sufficient to reproduce one of the standard flat images of the 3D object. As an example one can give here the schematic image of the Universe (in other words, the Metagalaxy) as a set of 'layers' of cubes of various colours, such that the colour of a cube is equivalent to

A A Vedenov Russian Research Centre 'Kurchatov Institute', pl. Kurchatova 46, 123182 Moscow

Received 19 May 1994
Uspekhi Fizicheskikh Nauk **164** (9) 967–978 (1994)
English text supplied by the author; edited by A Gelbtuch

the average volume density of galaxies (in a given cube), as shown in Fig. 5. However, such a flat image cannot be used to represent the data for the space positions of all galaxies constituting the Universe; here we need a stereo image, such as is shown in Fig. 6.

Nowadays the simplest way to look at a 3D computer copy of an object is to produce stereo slides (or some other form of stereo representation) of the copy and then use one of the devices for individual or collective viewing of the stereo image.

2. Stereo images and stereoscopic vision

The word 'stereoscopic' derives from the Greek stereo (solid) and scopos (watcher). A stereo image or a stereo pair consists of two images of the same subject. When the stereo image is viewed with a stereoscope (and after some practice without any device), the depth of image one perceives is the same as if one viewed the real subject itself.

Any form of photographic process, subject to the laws of refraction of light (electronic beams, x-rays, etc), creates in the photosensitive material a severely distorted, strongly compressed in depth 'copy' of a 3D object. Hence the problem has arisen how to fix and see an undistorted copy of a portion of the three-dimensional world. One way of solving this problem is to use stereo images: stereo photography, stereoscopic microphotography with scanning electron microscopes, etc (holography is essentially a variant of stereoscopy and solves the same problem: how to see an image fixed in a photosensitive layer as the true copy of a real object or scene [8]).

It is not difficult to produce a single stereo pair. For example, to construct the stereo image of a transparent cone one needs only a sheet of stiff white paper (say, 9.5 cm × 7.0 cm) and draw on it two circles around a coin, with the centres of the circles placed 6 cm apart and 2.5 cm above the lower edge of the paper. Let us now draw two points displaced, respectively, 1 mm to the right and 1 mm to the left from the centres of the left and right circles (so that the distance between these points is 5.8 cm). Then viewing the sheet in a standard stereoscope we can see a transparent cone: round edge of the base of the cone and (nearer to us) the apex of the cone. If the paper used for the stereo picture is opaque, then it must be viewed in scattered light, penetrating through a slit into the stereoscope; to view the stereo picture in transmitted light it must be drawn on a transparent foil or parchment.

If, instead, we move these two points further apart so that the distance between them is now 6.2 cm, we see a transparent cone with the apex remote from us.

Many people can fuse a stereo pair without the use of a stereoscope.

Let us now construct some more simple stereo pictures, which can be viewed in a standard stereoscope. For example, we shall see a segment inclined in depth if we joint the apexes of the cones in the previous example in the right and left halves of the stereo image with one of the ends (the upper, for example) of the vertical diameter of the circles. A truncated pyramid can be constructed by displacing a small square inside a large one to the left in one half of the stereogram and to the right in the other half of the stereogram. We perceive a rectangular box resting in the horizontal plane if we displace the squares representing the rear side of the box with respect to those representing the front side. Finally, let us construct a number of segments inclined in space in such a way that the end of one segment coincides with the beginning of the next one. In this way one can build broken line in space and even tie it into a knot.

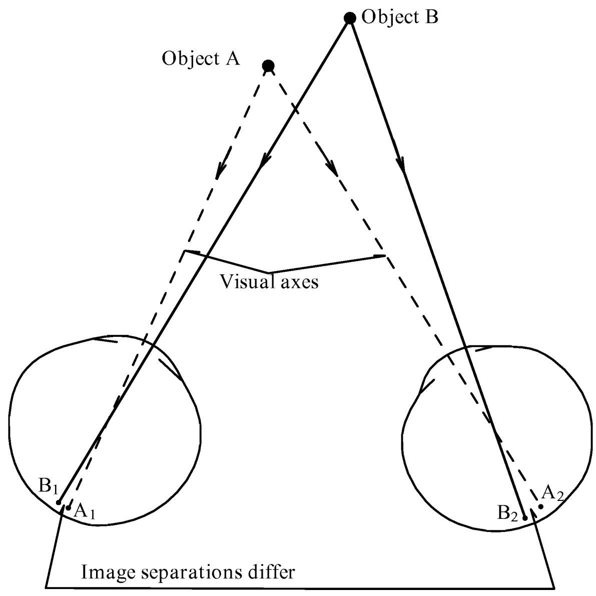

Figure 1. Retinal disparity.

What is stereoscopic vision? If a person looks at a small object A in front of him, we say that the observer 'fixates the object'. The rays going from A through the lens of the eye focus on the retina in regions A_1 and A_2 (Fig. 1). In the observer's mind the two images 'fuse' into one percept. The angle between the 'viewing axes' $A - A_1$ and $A - A_2$ (angle of convergence) and the difference between the positions of the images A_1 and A_2 relative to the centres of the retinas of the left and right eyes (retinal disparity) are the measures by which the observer judges his distance from object A.

The rays from a second object B focus on the retina in regions B_1 and B_2; the angle of convergence and the retinal disparity have different values, and the observer perceives object B as being at a different distance than object A. If the observer perceives objects A and B as belonging to one subject, this gives rise to a natural sensation of the depth of this subject.

Studies of the vision of man and of animals have shown that for the perception of depth two phenomena are important: accommodation and vergence.

Accommodation of the eye is its ''adaptation to clear vision of subjects at various distances; with the aid of eye muscles the shape of the lens is changed so that the image of the subject on the retina becomes sharp'' [9].

''Viewing of near objects forces the eye to accommodate to a greater extent than is nessesary for fixating points that are more remote. The difference in the muscular effort required for the accommodation of the eye allows us to see and judge the distance to various objects also by monocular vision. However, the estimate of distance derived from monocular vision is very imperfect and limited. When the target is further away than 6–8 m the eye does not accommodate any more. Therefore the ability to see and to evaluate accurately the distance of subjects and their parts is based mainly on binocular vision.

"In addition to accommodation, cues to binocular depth perception are provided by convergence movements and the discrepancy of images on the two retinas. Convergence movements are eye movements that bring together the visual axes of both eyes on the fixated object. Because the eyes are spaced some distance apart (about 60 mm), they see the object from slightly different points of view, which gives rise to the discrepancy of the images on the retinas" [9].

However, "convergence and accommodation do not play a main role in stereoscopic vision. This is demonstrated by the well-known Hering experiment involving judging the distance of a dropping ball. Through a pipe, which hides from us the whole surrounding scene, we fixate with both eyes some target, for example a chalk ball suspended on a thread. The experimenter then drops another white ball so that it passes ahead or behind the fixated point. Since we view this binocularly, we have no difficulty in deciding whether the ball has passed ahead of or behind the fixated target. But the time of passage of the ball through our field of view is less than the time required for accommodation or vergence movements. Hence, we can judge distance without either of these cues" [9].

One of the main factors in stereopsis is the retinal disparity of the images received by the two eyes. "However, not every kind of retinal disparity entails the impression of three-dimensionality of an object. If the disparity is too great or if the target produces in one eye an image on the left-hand side of the retina and in the other eye an image on the right-hand side of the retina, then we see the target as double. Let us take two needles and place them about 15 cm apart, one behind the other. Let us fixate the nearer needle, located at point c (Fig. 2), then the more remote needle (placed at point a), will be seen as double, at points a′ and a″. If we fixate the more remote needle (again placed at point c), the nearer needle (placed at point b) will produce two images, at b′ and b″. As can be seen from Fig. 2, in both cases the image of the needle that is not fixated falls on different halves of the retinas. Conversely, if the disparity is

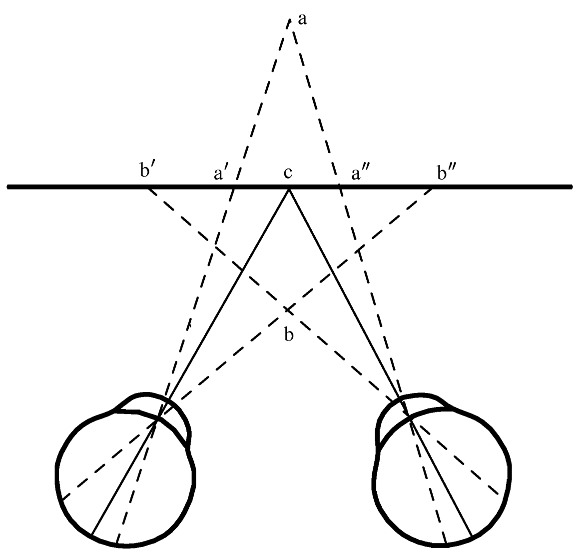

Figure 2. Experiment with two needles.

not too great or it is unilateral (so that the disparity points in the retinas of both eyes are in the right-hand sides of the retinas or their left-hand sides), then doubling of the image is absent. Instead one gets an impression of a third dimension, i.e. that the object is nearer or farther than the fixed point. The degree and the direction of the perceived distance of the object depend in this case on the so-called binocular parallax" [9].

The binocular parallax p of a visible point A is equal to the angle A_1AA_2 (see Fig. 1), and for small p ($\ll 1$)

$$p = \frac{d}{l}\,, \tag{1}$$

where d is the spacing between the pupils of the eyes and l is the distance to point A. The relative binocular parallax $\mathrm{d}p$ of two points A and B is

$$\mathrm{d}p = d\frac{\mathrm{d}l}{l^2}\,, \tag{2}$$

where $\mathrm{d}l$ is the difference between the distances to A and B. "If the difference between the angles, made in both eyes by fixation lines and the direction from a given (not fixated) point through the nodal point of the eye produces an angle in the temporal half of the retina, we see the given point as located closer than the fixated point. If this difference gives an angle in the nasal half of the retina, this point appears to be further away than the fixated point" [9].

As in the case of other senses of man (for example, touch, hearing, etc.), there is a threshold in stereo vision. To distinguish the spacing of two points, the difference in their depth must be greater than the threshold. The threshold for binocular parallax equals 5 – 10 arc seconds.

This threshold defines a limiting distance, the so-called radius of stereoscopic vision, above which the eye is no longer capable of recognising differences in relief. According to formula (1), the radius of stereoscopic vision for different people varies in the range 1 – 1.5 km.

3. Stereoscopes

The stereoscope appears to have been invented around 1830, before the appearance of the first 'daguerrotypes' (1839). "In the first stereoscopes, before the invention of photography, only drawings of geometric bodies and simple perspective drawings were placed" [10]. A description of the various types of stereoscopes used in the past can be found, for example, in Ref [1].

In Russia at the beginning of this century high quality stereophotographs were produced (in particular, for geography and zoology textbooks), which were usually viewed through so-called stereo lorgnettes.

Today there is a range of commercially available stereoscopes, both in Russia and abroad. Stereoscopes are used to view colour stereo slides, produced by stereophotography of landscapes, cities, architectural monuments, fairy tale toy models, models of technical devices, etc.

Stereoscopy is also used in various fields of science (see list of applications in Section 8).

The stereoscope is constructed so that each eye sees only one picture of the pair. If these pictures correspond to what each eye can see when viewing a real object, then the observer has the impression of seeing a real object, extended in depth.

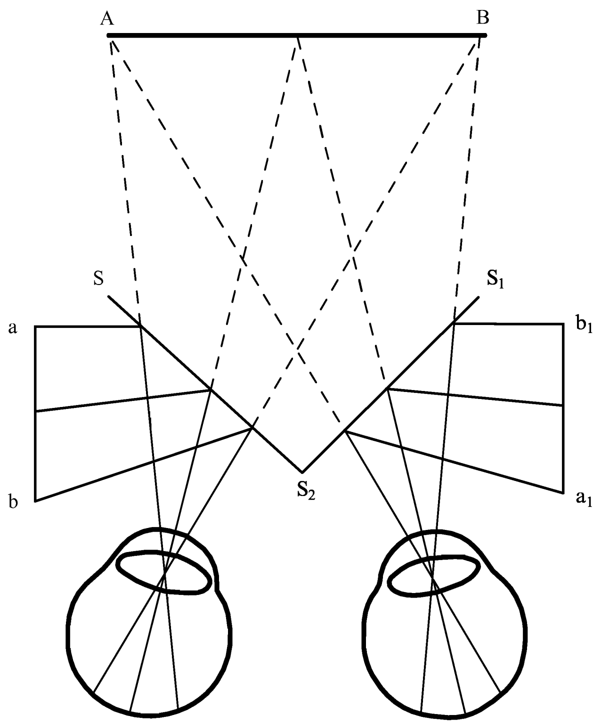

Figure 3. Wheatstone stereoscope.

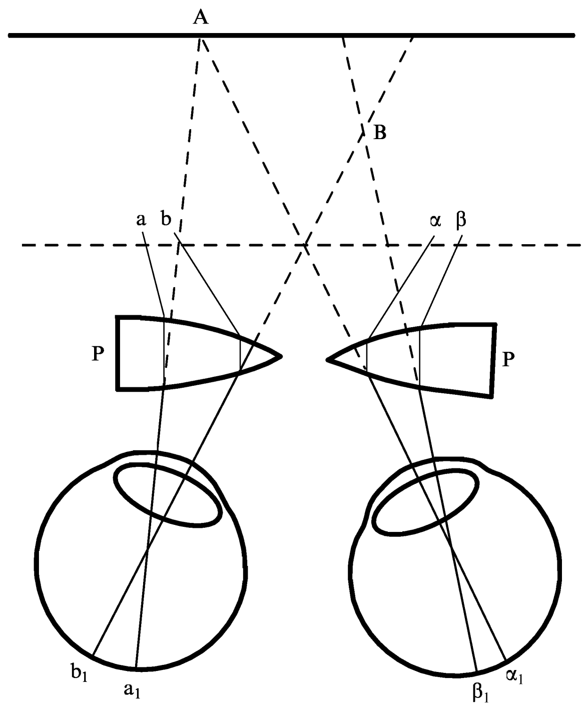

Figure 4. Brewster stereoscope.

''The first stereoscope was invented by Wheatstone in 1833. It consists of two mirrors placed at right angles to each other (Fig. 3). In front of one of the mirrors is placed a picture of the object in a projection seen by the left eye, and in front of the other mirror a picture of the object in a projection seen by the right eye. The first picture, reflected by the mirror, is visible by the left eye of the observer, the second by the right eye. By moving the pictures in front of the mirrors it is possible to adjust their position so that their centres fall on the corresponding parts of the retinas in the two eyes. In this case the unilateral disparity of the other parts of the pictures gives the impression of relief. In the plane A – B we then see a single, stereoscopic image of the object.

Another stereoscope that is quite widespread is the Brewster stereoscope (Fig. 4). Two pictures corresponding to the projections of the object received by the left and the right eye, are placed in ab and $\alpha\beta$. When viewed by both eyes through lenses P, they give a stereoscopic image in the plane A – B'' [9].

The stereo lorgnette consists of spectacles with lenses of approximately +6 dioptre, i.e. focal length about 16 cm, fixed to a handle. By turning the lens mounting around the point at which it is fixed to the handle it is possible to change the distance between the centres of the lenses, choosing the most convenient one for each viewer.

Still in the past century, Helmholtz designed a telestereoscope for topographical and military purposes: ''A device for determining which distant objects are ahead of others. Two mirrors are located in the front part of the eye pieces...; in one line with the mirrors, to the right and to the left of them, two further mirrors are placed that reflect the images of the objects to the first mirrors. Each eye receives an image of the distant object. If the ruler, at the ends of which the more remote mirors are fixed, is 1–1.5 m long, then it is possible to judge, for example, which hilltop, seen alongside others, is nearer to the observer'' [10]. In this case, however, ''the depth relief becomes magnified and this can lead to a disruption of the image of subjects close to the observer's eyes'' [10].

''It would be possible to extend the radius of our stereoscopic vision and in general to improve sharpness of the relief and resolution of the image by increasing the relative binocular parallax for the points of the object that we want to distinguish stereoscopically. According to equation (2), by increasing the distance between pupils d, we also increase dp. This is, in fact, what the Helmholtz teleostereoscope does'' [9].

''With an increase of the distance B between the objectives of the instrument, the radius [of our stereoscopic vision] increases as the ratio of B to the distance between the eyes d. The ratio B/d is called the relative plasticity of the device. If the device also magnifies by a factor w, then both the binocular parallax threshold (10 arc seconds) and the total plasticity of the device increase by the factor w''. Usually, in the focal plane of stereoscopic range meters there are ''stereoscopic photographs of a series of vertical landmarks located at fixed distances from the observer. Viewing through such a range meter we have the impression that the landmarks extend in depth, and this allows us to estimate the distance of points in the observed landscape from the position of the nearest calibrated landmark'' [11]. At present such devices, which are now called hyperscopes, are used for the study of perception of three-dimensional space by man.

''The increase in the effective distance between eyes increases the retinal disparity of images formed on the retinas and the difference in convergence angles, when you look from one object to another at a different distance. Suppose you look at A through the hyperscope while B is also in view. The new disparity of separation between the images of the two objects on the retinas forces you to perceive greater depth between them. You also perceive greater depth because the difference in convergence angles is now greater.

''The hyperscope also alters the apparent height and width of nearby objects. In normal vision you are accustomed to a certain relation between the size of an object's image on the retina and the object's distance as implied by the convergence of the eyes when you look at it. Seen through the hyperscope an object looks smaller because the angle of convergence required to see it through the mirrors is larger than normal.

''Many other familiar objects take on a strange appearance through the hyperscope. For example, a person's face looks thinner and seems to have a prominent nose. All the objects immediately return to their normal appearance if you close one eye while still looking through the instrument with the other one. Because you are no longer able to compare retinal disparity or convergence angles between the eyes, you are left with only the pictorial cues about depth'' [6].

These effects seen when real objects and scenes are viewed in a hyperscope, can also be seen in a stereoscope, when viewing a stereo pair taken so that the distance between the stereocamera objectives is greater than the distance between the eyes.

If the stereogram of an object is black-and-white or gray-scale halftone, then to perceive the effect of volume one can colour one half red, and the other half green and view the resulting anaglyph through red – green spectacles. Instead of a computer or a TV screen, one can use a white paper screen and project onto it the red – green image. Such a red – green anaglyph can also be printed on white paper. In all such cases red – green spectacles are necessary.

Another way is to alternate the left (green) and right (red) halves of a stereo pair on the screen of a computer and look at them through red – green glasses.

One can combine the use of polarisation filters when projecting the two halves of a stereo image with the use of corresponding polarisation filters in spectacles. This method makes it possible to view in full colour stereo images of any size, 'hanging in air', by projecting the stereo image on a special screen that retains polarisation in the reflected light.

A modern device for viewing colour stereo images that holds promise for the future incorporates liquid-crystal (LC) stereo spectacles, controlled by a personal computer. Here, the alternating appearance of the left and right halves of the stereo image on the computer screen is synchronised with the opening and closing of left and right shutters in LC stereo spectacles (Yu V Devyatkin et al., Microcosm, Moscow).

Any spectacles (red – green, polarised, or LC) make possible the collective viewing of stereo slides or stereo movies.

A comparison of 3D technologies, such as holographic stereograms, varifocal mirrors, stereo pairs, and alternating pairs for displaying cartographic data is presented in Ref. [4].

4. Stereo postcards, integral photography, and holography

Viewing of 3D images of objects without the use of stereoscopes has been under consideration from the beginning of this century. The techniques put forward include integral photography, lens raster images, holography, and other methods [1, 2].

From recent results one should single out the applied work carried out at the Yaroslavl Pedagogical Institute (G V Zhus, S V Turundaev) and the Illinois Institute of Technology ('phscolograms' of Helen Sandor).

Computer holograms are being studied in the MEDIA Laboratory of the Massachusetts Institute of Technology (S A Benton), the Moscow Institute of Problems of Transfer of Information (A Yaroslavskii et al), and the University of Alabama (J Caulfield).

5. Photostereo algorithm

How does one construct a stereo image? Suppose we view a parallepiped along its horizontal axis Oz, the parallepiped lying in the horizontal plane Oxz, rotated around the vertical axis Oy, and its nearest vertex coordinates are 0, 0, 0. Suppose that the image generated on the retina of each eye is the same as in a photo camera placed at that eye. Then the coordinates of projections of the vertex x, y, z in the focal plane, i.e. on the retinas of the left and right eyes, are

$$x_L = F\frac{x-d}{1-z/L}\,,$$
$$x_R = F\frac{x+d}{1-z/L}$$
$$y_L = y_R = y_1 = F\frac{y}{1-z/L}\,, \tag{3}$$

where L is the distacce from point 0, 0, 0 to the middle of the line joining the eyes, F is the focal length of the camera, and d is the distance between the pupils. Therefore the stereo image of point x, y, z is a pair of points on the screen with the coordinates (u_L, v) and (u_R, v)

$$u_L = X_0 + R + mx_L\,,$$
$$u_R = X_0 - R + mx_R\,,$$
$$v = Y_0 - my_1\,, \tag{4}$$

where X_0, Y_0 are the coordinates of the centre of the screen, R is the distance between the left and right halves of the stereo pair, and m is the magnification factor.

By changing parameter R one can choose the most comfortable conditions for viewing the image.

6. Finding the space coordinates

There is a number of physical methods for determining the space coordinates of different objects: radar, sonar, and lidar measurements; acoustic, x-ray, and seismic methods; tomography, interference photography, etc.

Of particular interest is the determination of space coordinates from a single photograph of the object, with account taken of the expert's knowledge of the nature of the object, its properties, and its features.

Suppose that we can approximate an object shown in an ordinary photograph with a known three-dimensional body (spherical ball, parallepiped, pyramid, etc) or with a combination of such bodies. Then by measuring the dimensions of the projections of these bodies on the photograph we can find the depth of the object and of its parts. Take as an example a simple building (see, e.g., Ref. [7]), whose form can be approximated by a parallepiped. Let the observer view the building from the ground. We need to measure (with a mouse, for example) the dimensions of the projection, on the computer screen, of the parallepiped approximating the building. For simplicity let us assume that the distance l (of the observer from the building) is much greater than the dimensions of the building; then for the depth z_1, z_2 of the side walls of the building we obtain the equations:

$$y_1 = y_0 \frac{l}{l + z_1}, \quad y_2 = y_0 \frac{l}{l + z_2}.$$

Hence for $dy_1 = y_1 - y_0$ and $dy_2 = y_2 - y_0$ we have

$$\frac{dy_1}{y_0} = \frac{z_1}{l}, \tag{5}$$

$$\frac{dy_2}{y_0} = \frac{z_2}{l}. \tag{6}$$

Because the parallepiped is rectangular

$$\frac{z_1}{x_1} = \frac{x_2}{z_2}.$$

From Eqns (5) and (6) we have

$$z_1 z_2 = x_1 x_2, \quad \frac{z_1}{z_2} = \frac{dy_1}{dy_2},$$

wherefrom we can find the depth of the sides of the building:

$$z_1 = \sqrt{x_1 x_2 \frac{dy_1}{dy_2}}, \quad z_2 = \sqrt{x_1 x_2 \frac{dy_2}{dy_1}},$$

and the distance of the observer from the building:

$$l = z_1 \frac{y_0}{dy_1}.$$

7. Examples

7.1a The Universe

The CfA catalogue [5] contains about 50 000 galaxies shown in Fig. 5 as a standard image of two parallepipeds, each cut into 5 horizontal layers (layers 1 – 5 and 6 – 10 in Table 1). Positive and negative declinations (−90 to +90 degrees) and latitudes (0 h 00 min – 24 h 00 min) are plotted along the horizontal axes of the parallepipeds, and the velocity (Doppler red shift) or distance on the vertical axis. The layers are divided into cubes, and the average density of galaxies in each cube is shown as a gray colour on a 16-grade scale.

The coordinates of the layers (in km s^{-1}) and the total number of galaxies in each layer are listed in Table 1.

Since the intensity of light from very distant galaxies, measured by a device on Earth, drops below the instrument threshold, an apparent 'edge of the Universe' can be seen. The dark, curved bands seen at nearly the same declination and lattitude in all layers, are partly due to light absorption of lack or observations in the Milky Way.

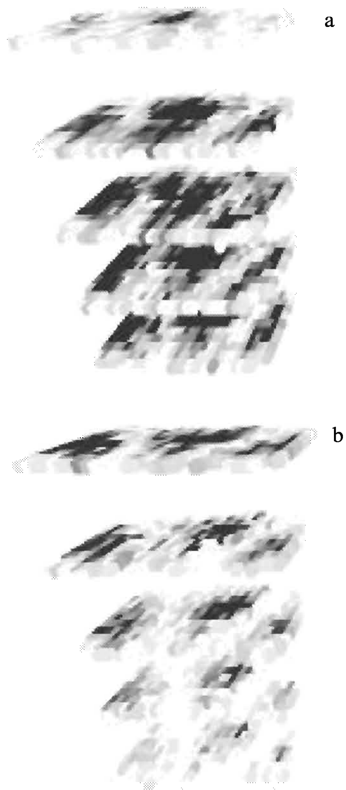

Figure 5. The Universe. (a) The near 5 layers; (b) the distant 5 layers.

7.1b 1/8 of the Universe (Fig. 6)

Approximately 1/8 of the Universe is shown as a stereogram of nearly 5 000 galaxies, represented as identical black points. Negative declination (0 – 90 degrees) is plotted along the vertical axis of the parallepiped, velocity (Doppler red shift) or distance along the horizontal axis, directed away from the observer, and longitude (12 h 33 min – 16 h 59 min) along the second horizontal axis of the parallepiped.

7.2 Screw instability plasma (Fig. 7)

This is a 3D reconstruction of one of the first photographs of screw instability of the plasma toroid with electric current in the external magnetic field. Such instabilities have delayed by 30 years the design of thermonuclear fusion reactors with magnetic field confinements.

7.3 Hot plasma in the fusion reactor model (Fig. 8)

A schematic diagram of the structure of the magnetic surface, confining the hottest region of plasma in T-10 installation, an experimental model of a thermonuclear

Table 1.

km s^{-1}	0	10	30	50	70	100	150	200	300	400	500	900
Layer	0	1	2	3	4	5	6	7	8	9	10	11
Number of galaxies	20951	1258	4573	5246	5044	5491	5786	3144	2859	1084	737	1510

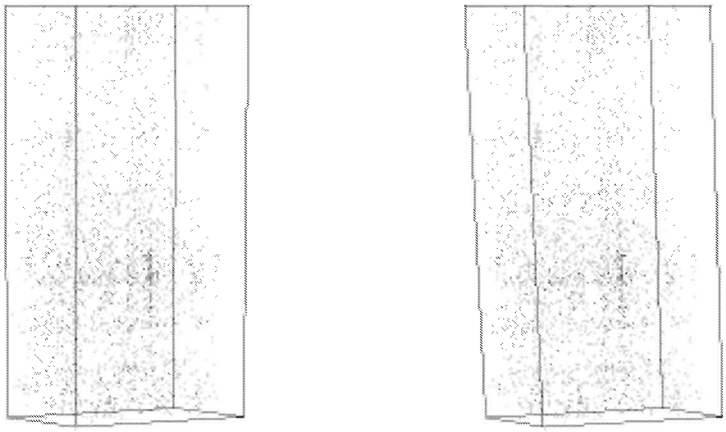

Figure 6. 1/8 of the Universe.

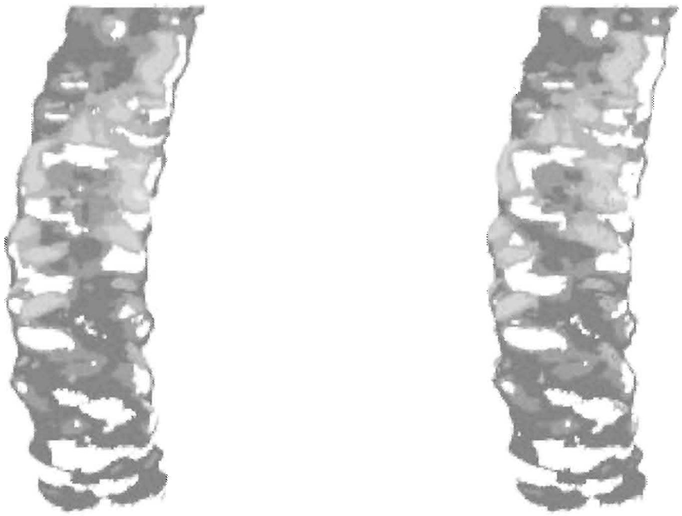

Figure 7. Screw instability of plasma.

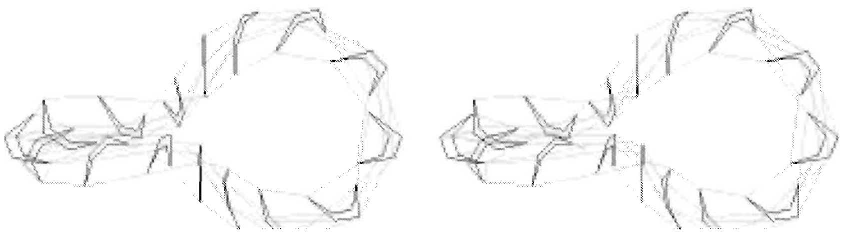

Figure 8. Hot plasma in an experimental model of a thermonuclear fusion reactor.

fusion reactor with magnetic field confinement. It is assumed that in a full-size thermonuclear fusion reactor the shape of the hot plasma will be the same.

7.4 Clay (Fig. 9)

The montmorillonite swelling clay consists of many parallel aluminium silicate lamellae about 10 A thick (with transverse dimensions of the order of 1 μm), separated by water layers of equal dimensions.

Each lamella consists of two layers of Si – O tetrahedra (Si in the centre of the tetrahedron, O in its vertices) interspersed by one or two (in different minerals) Al – O octahedron layers (Al in the centre, O in the vertices of the octahedon). The bottom part of the vertices lamella is shown schematically in Fig. 9. Hydrogen bonds extend downwards from the layer of the tetrahedra towards the layers of water.

The approximate equality of the dimension of the hexagonal structure (in the plane of the Si – O layer) and the dimension of the periodic structure of ice-1 (in the plane of the water layer, parallel to the Si – O layer) is the main cause of the capacity of the clay to swell. The second

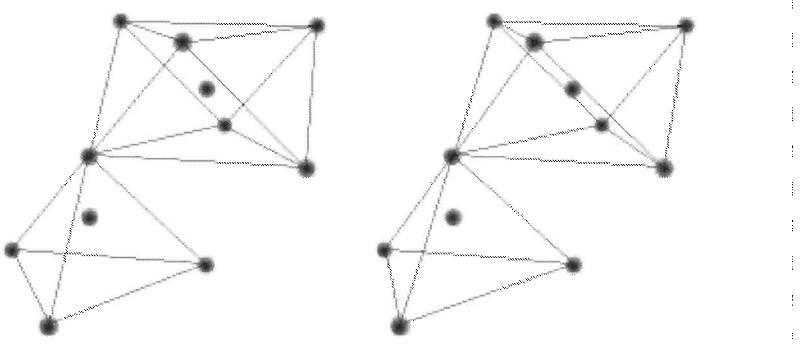

Figure 9. Element of clay structure.

necessary condition for swelling is the existence in the natural clay minerals of Mg^{2+} impurities (substituting for Al^{3+}) or Al^{3+} impurities (substituting for Si^{4+}). These impurities create a negative electric charge in the lamella, which leads to the appearance of 1-, 2- and 3-valent cations — Na, Ca, and Fe — in the water layer between the lamellae.

The thickness of the water layer is governed by the balance between the van der Waals forces, electrostatic forces, and osmotic pressure. It depends on salt concentration in water and ranges from 0 to 100 A. Alternating layers of aluminium silicate and water form lamellar structures up to a fraction of a micrometer thick.

7.5 Antigen – antibody contact (Fig. 10)

How does an antigen bind to an antibody? The mechanism of their interaction has been discussed in scientific literature for many years. In 1986 molecular structure data for an antigen – antibody complex were published for the first time: the antigen was the protein lysozyme (Lys), and the antibody in this case was one of blood immunoglobulins, named Fab.

The analysis of the set of amino acids in the area of contact of these two macromolecules has shown that the area of contact is a nearly flat irregular closed curve, a 'ring' with a diameter of 30 A and a 'thickness' of 5 A. The points represent the centres of segments joining atoms of the carbon chain of the antigen Lys to atoms of the carbon chain of the antibody Fab, spaced not more than 6 A apart. Thus, here the area of contact of the two macromolecules is a line in space, not a 'hand-and-glove' contact (two adjacent closely fitting surfaces) or an 'uneven stone – plane' (three-point) contact.

7.6 The tobacco mosaic virus

The tobacco mosaic virus (TMV) is, historically, the first virus that has been discovered, and one of the first viruses whose molecular structure has been fully established. It consists of a helical protein tube (external diameter 180 A, internal diameter 40 A, length 3000 A) and of RNA, wound helically over the inner surface of the tube. The protein tube consists of 2130 identical protein molecules (Fig. 11), stacked in a right-handed helix (49 protein molecules per three windings of the helix) with a pitch of 23 A (Fig. 12).

In vitro, at different values of pH and ionic strength, other aggregates occur instead of the tube: a long helical aggregate; an aggregate with 52 rather than 49 subunits in three turns; a protein disk with 34 subunits, or a helix with 38 subunits with a little over two turns; disks and aggregates of disks; and mixtures of small oligomers.

The TMV virus is, as any other virus, a purely physical object (at least outside of the cell of the plant in which it reproduces). From the physical point of view TMV is a giant molecule with a definite arrangement of atoms in space. The study of the structure of TMV, of its motion, passage through various microscopic barriers, binding to surfaces, degradation, etc., is a subject that belongs to

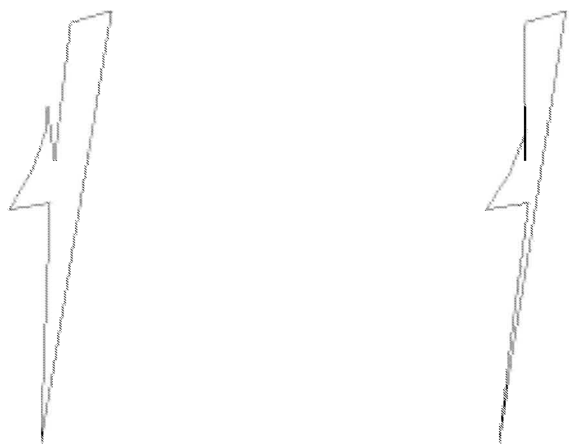

Figure 10. Line of antigen – antibody contact.

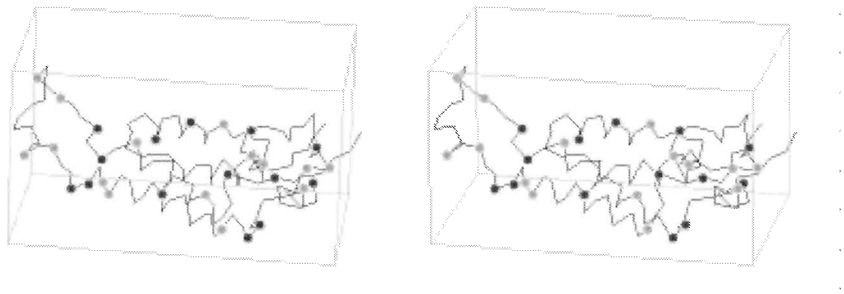

Figure 11. The TMV protein.

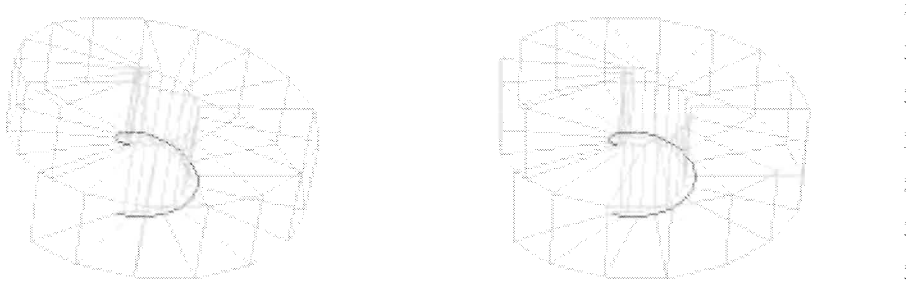

Figure 12. Part of the helical protein tube of TMV.

conventional fields of physics. The same is true of problems relating to the observation and diagnostics of the type and concentration of the virus and of its filtration.

7.7 3D reconstruction of a quasicrystal specimen (Fig. 13)

The starting material for the reconstruction was the photograph by An Pang Tsai, Akihisa Inoue, and Tsuyoshi Masumoto (Tohoku University) from the article by P W Stephens and A I Goldman: ''The structure of quasicrystals'' [*Scientific American* **264** (4) (1991)].

7.8 'Sir Isaac Newton' (grey-scale version) (Fig. 14)

The reconstruction is based on the portrait by Godfrey Kneller [*Scientific American* **244** 122 (1981)] and a photograph of a bas-relief, presumably by J Wedgwood, drawn from S I Vavilov's biography of Isaac Newton published in Moscow in 1945.

8. Reconstruction of a 3D scene from a stereo image

So far we have discussed the construction of stereo images. There is, however, also the inverse problem: analysis of a digitised stereo pair leading to the reconstruction of the 3D object or scene represented by it.

In scientific work the simplest (next to conventional photography) method of fixing information about an object under study is to make simultaneously two photographs from different positions, in particular to take a stereophotograph of the object.

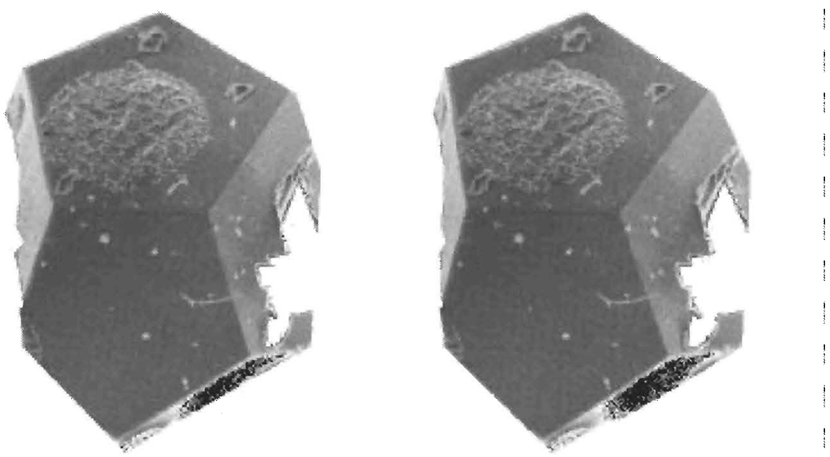

Figure 13. 3D reconstruction of quasicrystal sample.

Figure 14. Stereo portrait 'Sir Isaac Newton' (grey scale version).

This method has for a lomg time been used in various areas of scientific research, such as:

materials science;
biology;
medical science;
fluid mechanics, particularly the study of explosion;
criminology and its applications;
architecture;
mathematics;
anthropology;
cosmology;
geography;
education.

Reconstruction of the 3D scene by stereo image analysis is also needed for the solution of a number of applied problems: remote determination of the relief of the Earth (or other planets) and of the bottom of the sea, autonomous navigation of moving robots, etc.

The main idea behind all methods used for solving this problem consists of finding corresponding (homologous) points on the left and right halves of the stereo image and measuring the distance between these points to define the local depth of the point in question.

For the solution of this task, various algorithms have been put forward in the past decade: hierarchical Marr–Poggio and Grimson algorithms, mutual amplification of equal- disparity points (the Prazdny algorithm), a number of neural net algorithms, 'form from shadow' and 'form from texture' algorithms, and fractal algorithms.

However, the problem is very complex and at the present time would appear to be far from solution, because for the understanding of a scene represented in a stereo image one needs in the computer memory an enormous amount of information from very different fields. Without such knowledge, analysis of an arbitrary stereo pair may be beyond our capacity.

This does not, of course, exclude the feasibility of creating a system of effective stereo image analysis for a limited subject area. This can be, for example, the analysis of relief, or the analysis of buildings or structures, belonging to definite (a priori known) categories.

In a number of cases for the reconstruction of the 3D structure of the object or a scene one needs only a limited number of homologous points. In this case a compromise is possible: the work is divided between man and computer. The man finds (working, for example, with a 'mouse') a number of important pairs of homologous points in a stereo pair on the computer screen, reducing the whole problem to a number of simple tasks.The remaining work is done by the computer. Another way is to divide manually the entire object or scene into parts and then to reconstruct the spatial positions of points in these parts automatically with the aid of one of the aforementioned algorithms (a similar method has been used for the solution of the 'traveling salesman problem' [12]). As an example one can quote the reconstruction of the carbon skeleton of the lisozyme molecule from its published stereo image [3].

With a scanner it is possible to input into a computer stereo images published in scientific periodicals and monographs (for example stereo images of various microworld objects [13]) and then create 3D representations of these objects.

9. Conclusions

A computer-generated three-dimensional representation of an object is a 'data base' which not only contains full space coordinates and brightnesses (or colours) of all points of an object, but also makes it possible to look at a complex object from a 'bird's-eye' point of view, and identify some features of the object as a whole.

As an old Chinese proverb says, ''one picture is worth ten thousand words''[14].

After creation in the computer of a 3D image of an object, it is possible to rotate it, zoom in and out, change the scale and colour, carry out different 'filtration' operations, and perform other transformations.

The ability to visualise invisible objects, such as temperature fields, intensities of radioactive or neutron radiation (in nature and in industry), etc., as three-dimensional images holds great promise for the future.

In conclusion I would like to express my gratitude to scientists without whose help this article could not have appeared. Files of atomic coordinates of the Lys–Fab complex were kindly provided by Yu P Lysov (Engelhardt Molecular Biology Institute, Moscow), the photograph of the plasma toroid and the results of measurements of the 3D structure of hot plasma by K A Razumova (Russian Research Centre 'Kurchatov Institute', Moscow), the red-shift catalogue with comments by V S Avedisova (Astrophysical Institute, Moscow), and information about the work at the Illinois Institute of Technology by A A Filyukov (Institute of Applied Mathematics, Moscow). To all of them I am sincerely thankful.

References

1. Valyus N A *Stereoskopiya* (Stereoscopy) (Moscow: Fizmatgiz, 1962)
2. Okoshi T ''Three-dimensional images'' *Proc. IEEE* **68** (5) 5 (1980)
3. Vedenov A A *Matematika Stereoizobrazhenii* (Mathematics of Stereo Images) (Moscow: Znanie, 1991)
4. Hodges L F, McAllister D F *Proc. SPIE Int. Soc. Opt. Eng.* **761** 146 (1987)
5. Huchra J P, Geller M J, Clemens C M, Tokarz S P, Michel A *The CfA Redshift Catalogue* (Version Feb. 1992)
6. Walker J *Sci. Am.* **255** (5) 124 (1986)
7. G Hatje (Ed.) *Encyclopaedia of Modern Architecture* (London: Thames and Hudson, 1975)
8. Unterseher F et al. *Holographic Handbook* (Berkeley, CA: Ross Books, 1982)
9. Kravkov S ''Stereoskopiya'' (Stereoscopy), in *Tekhnicheskaya Entsiklopediya* (Technical Encyclopedia) (Moscow: Sovetskaya Entsiklopediya, 1927–1933)
10. Brockhaus F A, Efron I A *Entsiklopediya* (Encyclopedia) (St. Petersburg, 1901)
11. Agafonov S ''Dal'nomery'' (Range meters), in *Tekhnicheskaya Entsiklopediya* (Technical Encyclopedia) (Moscow: Sovetskaya Entsiklopediya, 1927–1933)
12. Lawler E L, Lenstra J K, Rinnooy Kan A H G, Shmoys D B (Eds) *The Traveling Salesman Problem: A Guided Tour of Combinational Optimisation* (New York: John Wiley, 1984)
13. Totrov M, Abagyan R *Structural Biology* **1** (4) 259 (1994); Rodgers D W, Harrison S C *Structure* **1** (4) 227 (1993)
14. Malkiel B G *A Random Walk down Wall-Street* (New York: Norton, 1973)