Autostereograms - Classification and Experimental Investigations

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Abstract. One important branch in computer graphics is the research for representing three-dimensional objects. Many different techniques have been developed to convey to a user of a two-dimensional medium that he sees a three-dimensional scene. Apart from realistic image synthesis, e.g., ray tracing and radiostiy, there are techniques which try to generate a real three-dimensional impression for the viewer.
In the last years a new technique to produce such pictures has gained popularity. The generated images are called autostereograms. An interesting feature with this technique is, that only single pictures have to be produced and that no additional equipment is needed to produce a three dimensional impression. Therefore autostereograms are also called "single image stereograms" (SIS).
This work gives an overview on the technique of autostereograms. After a short description of the algorithms to generate autostereograms a detailed classification is introduced. After that the perceptability of autostereograms and software related to the topic is discussed. Moreover, experiments with animated autostereograms will be presented. Finally some experiments concerning the usage and change of colors in autostereograms and the combination of two depth-scenes within one image will be discussed.

1 Introduction

First the general idea of autostereograms is described. The human eyes use two mechanisms to produce sharp pictures. The eyes can be focused at a point in a 3D scene, which means that the lenses in the eyes are adjusted so that a sharp image of the 3D point is generated on the retina of the human eye. On the other hand the eyes can be aligned so that the lines of sight intersect at some specific point in the 3D scene. This adjustment of the eye angles is called convergence. Usually the convergence and the focus are synchronized and happen simultaneously.

Because of the different positions of the two eyes, they deliver slightly different pictures to the brain. The differences in these pictures can be used to reconstruct the three-dimensional scene.

If a virtual three-dimensional scene should be shown, the eyes have to see two different images, which are called stereograms. In an autostereogram these two pictures are combined in one single image. To divide the two pictures, each eye has to look at a different part of the image. This can be done, if the eyes look "behind" the image. That means that the convergence is adjusted behind the autostereogram, but the focus has to be adjusted at the image plane to see a sharp picture. Therefore the convergence and the focus have to be "decoupled".

2 Generation of autostereograms

The main effect that is responsible for the perception of a three-dimensional scene in autostereograms is stereopsis. Because of the different positions of the eyes different images are perceived. Each projection of a three-dimensional point is shifted for a precise amount, which is dependent on the distance of this point to the image plane. A detailed explanation of the generation of autostereograms can be found in [Thim94].

Autostereograms have been also dealt with in [Kins92], [Thim93], [Tonn95], and [Tyle90].

In Figure 1 the eyes are focused at a point in front of the eyes. Between the 3D scene and the eyes a projection plane is given. Each point P of the 3D scene projects to two points P_l and P_r on the projection plane. The distance s between these points corresponds to the amount of shift in the two images, seen by the left and right eye respectively.

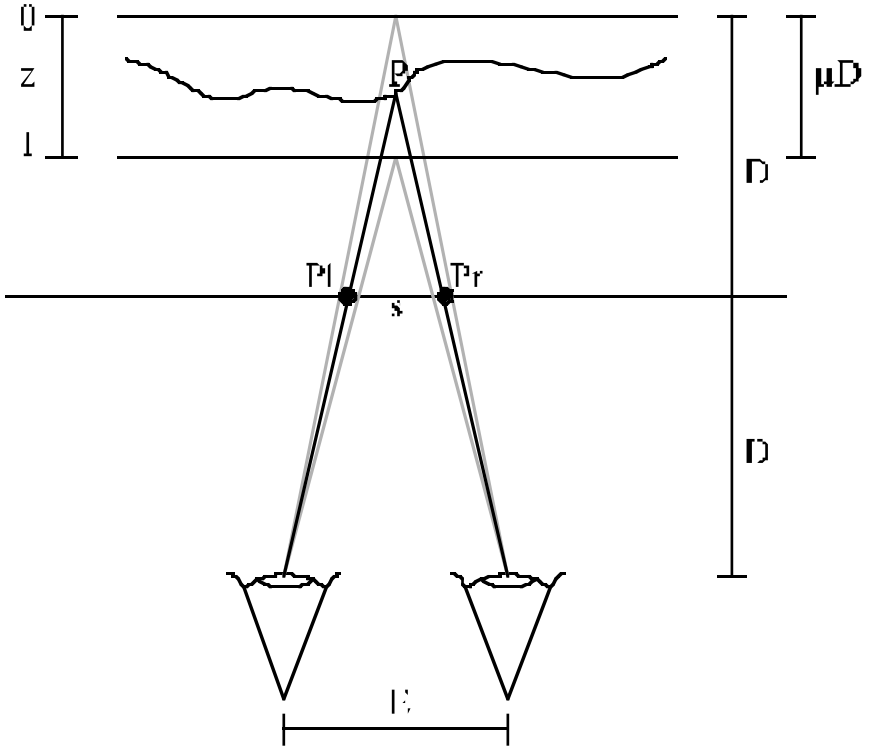

Fig. 1. Point P seen at position P_l and P_r by the left and right eye respectively.

The distance s, which is also called seperation, depends on the depth of point P in the 3D scene. For each point of the object scene the corresponding difference s between P_l and P_r has thus to be calculated. The following assumptions are used to get simpler formulas [Thim94]. The maximum depth of the scene should be twice the distance D between the eyes and the projection plane. The point of the object scene closest to the viewer is at most μD (μ is typically 0.33) away from the maximum distance D. This interval should be parametrized with the variable z, which has values from 0 to 1. With these assumptions a formula for the seperation s can be derived as [Thim94]:

$$s = \frac{E \cdot (1 - \mu \cdot z)}{2 - \mu \cdot z}$$

Of course this formula is exact only for the special case, where the point P lays exactly in front of the eyes, but the errors for all other cases are negligible.

Now it is explained how to produce an autostereogram. In Figure 2 a test scene is shown. To recognize that the two points A_r and A_l on the projection plane belong to the same point A in the scene they have to be depicted with the same color. The problem is that the left eye also sees the point A_r of the right eye and vice versa. Therefore these "false" points have to be used for the other eye, too. To do this, rays are shot through these points into the scene and they hit other points in the 3D scene (i.e., B and C). Therefore A_r is also B_l and A_l is the same as C_r. Therefore points B_r and C_l have to be assigned the same color as A_l and A_r and dependencies are produced along a horizontal scanline.

The next step is to design an algorithm to compute an entire image. The eyes have the same horizontal height, therefore the color dependencies are produced only along one horizontal line. That means that the picture can be calculated line by line.

One pixel in a line can be connected with not more than two other pixels, because it can be used ether as a right or a left projection point. Therefore these connections (dependencies) can be stored in a dependency array. Each pixel has an entry, which denotes with which other pixel it is connected. If the array is built it is very easy to draw the pixels of a line. The colors of those pixels, which have no entry in the dependency array can be chosen arbitrarily and all others have to get the same color as the pixel with whom they are connected.

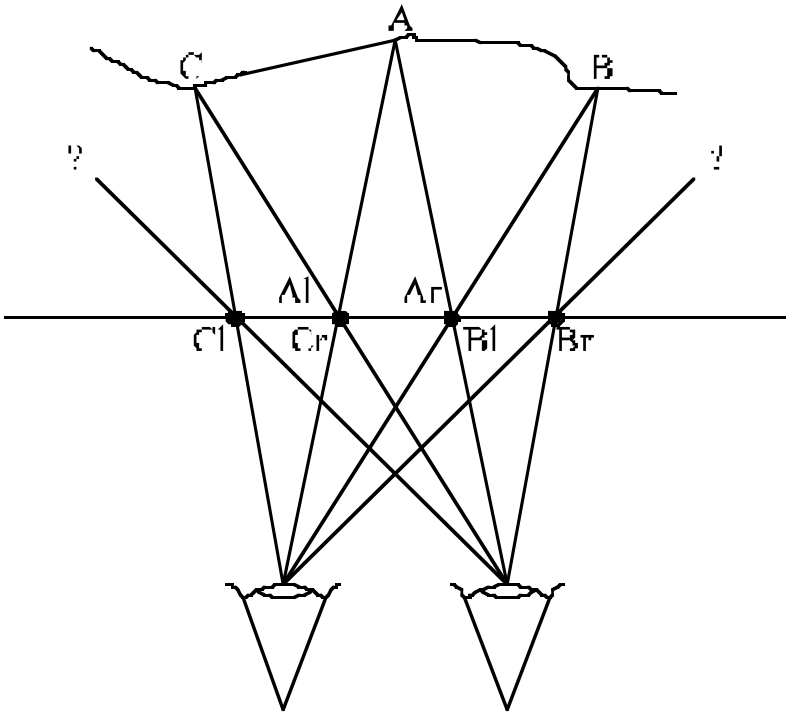

Fig. 2. Color assignment, same color for C_l, $C_r = A_l$, $A_r = B_l$, B_r.

At last it has to be explained how the array of dependencies is built. One method, which was developed by Thimberly, Inglis and Witten in [Thim94], is that for each point (x, y) in the image, the seperation s is calculated. Now the pixels at (x+s, y) and (x-s, y) must get the same color. Therefore the entry in the dependency array at position x-s is a reference to the pixel x+s. These chains of dependencies determine the color selection within one scanline.

If at a given pixel there is a dependency then the color of the corresponding pixel is taken, otherwise, e.g., a 2D texture might be taken to determine the pixel color value. High frequency 2D textures are preferable as they allow to distinguish easily between different positions of object space.

3 Classification of autostereograms

In the literature only a rough classification of autostereograms can be found. Only two classes are mentioned, namely SIRTS (Single Image Random Text Stereogram) and SIRDS (Single Image Random Dot Stereogram) [Ingl95]. Therefore a more detailed classification is given in the following.

3.1 SIS - Single Image Stereogram

The expression SIS ("single image stereogram") is used as another word for autostereograms. This type of stereogram consists of only a single image and can be viewed without any technical aid.

3.2 SIRDS - Single Image Random Dot Stereogram

This category contains the well known, colorful pictures, which are printed and sold in millions on posters, postcards and books. The images consist of more or less random, varied patterns, which are repeated with some distortions over the whole picture area. The words "random dot" do not mean that the texture has to be a random noise picture. It is also possible to use a predefined texture. But the term "random" should express that the pattern has no context to the three-dimensional scene.

The class SIRDS can be split up in two subclasses: SIRMDS (Single Image Random Monochrome Dot Stereogram) and SIRCDS (Single Image Random Color Dot Stereogram).

Because of their simplicity and possibility to to be easily produced on a monochrome medium, SIRMDS are used in many programs. For the commercial use SIRCDS are more attractive.

3.3 SIRTS - Single Image Random Text Stereogram

The pictures of this class consist only of ASCII- characters. The advantages are that it is possible to print these images without a graphical display or high quality printer. They are very simple to produce, save, and transmit.

Of course it is also possible to produce SIRTS with and without color: SIRMTS (Single Image Monochrome Text Stereogram) and SIRCTS (Single Image Color Text Stereogram).

3.4 SICDS - Single Image Context Dot Stereogram

A special variation of SIRDS are SICDS. The main difference is that the texture is connected with the three-dimensional scene. Therefore the autostereogram is a two-dimensional representation of the scene, but, when viewed stereoscopical, a real three-dimensional picture arises. SICDS can be split up in SICMDS (Single Image Context Monochrome Dot Stereogram) and SICCDS (Single Image Context Color Dot Stereogram).

3.5 SICTS - Single Image Context Texture Stereogram

Analogous to the SICDS the texture of a SICTS is connected with the 3D scene. Because the texture consists only of ASCII-characters these characters have to be selected to form a more or less realistic scene. Again a more detailed classification can be made to distinguish SICMTS (Single Image Context Monochrome Texture Stereogram) and SICCTS (Single Image Context Color Texture Stereogram).

4 Autostereograms and perceptability

For many people it is somewhat difficult to see the 3D scene of an autostereogram. Along with different viewing techniques (e.g., staring through the picture, looking at a wall behind the picture, ...) it is possible to find an order of autostereograms relating to how easy they are to see. There are different factors that are important. The main problem is that the brain has to find the two corresponding marks (pixels, characters) in the picture and superimpose them. This is easier if only corresponding marks look the same and all others are different. One possibility to make them distinct is to vary their color consistently. Only the two corresponding marks should have the same color. Therefore colored images are easier to see than monochrome ones.

Another distinguishing feature is the texture. On one hand it should vary as much as possible (high frequency textures) to avoid that the viewer superimposes non corresponding pixels. On the other hand it is helpful if there are some bigger, distinct and corresponding structures in the autostereogram, which are easier to superimpose than unstructured areas. This is a reason for the fact that ASCII-Stereograms are very easy to see.

The different types of autostereograms can be ordered with respect to ease of perceptability. This order may differ somewhat from one observer to another and depends also on a specific picture, but after various experiments the following order has been shown to reflect the general situation: 1. SIRCTS and SICCTS, 2. SIRMTS and SICMTS, 3. SICDS, 4. SIRCDS, 5. SIRMDS

5 Software related to autostereograms in the internet

The internet has become an important media for information exchange. It contains very much data, but this information is not always easy to find because of the inherent distributed storage among different servers. Besides the information is often changed and modified, therefore only a temporary state can be presented. Most of the discussion about autostereograms takes place in the newsgroup "alt.3d" and sometimes in "comp.graphics". The most important ftp- and http-addresses which contain information on autostereograms and images are currently:

ftp://katz.anu.edu.au/pub/stereograms
ftp://ftp.amu.edu.pl/pub/chemia/stereoskopia
ftp://ftp.cs.waikato.ac.nz/pub/SIRDS
http://www.cs.waikato.ac.nz/~singlis/sirds.html
http://h2.ph.man.ac.uk/gareth/sirds.html

6 Animating autostereograms with AVS

Many programs on the internet, which produce an animation sequence of autostereograms, are not very flexible or user friendly. They often show only a sequence of predefined pictures and most of them produce only SIRMDS. To explore animated SIRDS, for example, an interactive program would be helpful.

In [Tonn95] a comprehensive survey of autostereograms is given and an experimental software implementation using the Application Visualization System (AVS) is described.

AVS [AVS92] is a commercial software system for scientific visualisation based on the data flow model. Each visualization problem is subdivided into elementary tasks, which are realized as modules. The user builds a network out of these modules according to his needs. The connections in such a network describe data exchange paths. There are many predefined modules, but it is also possible to generate user defined modules.

Basically a module concerning the generation of autostereograms was incorporated into the AVS system (see Figure 3). The main part to produce an animation with SIRDS is realized with a module *sis* that transforms a depth image into a SIRDS. The depth image contains a 3D scene, where the distance of a point in object space with respect to the viewing plane is encoded with grey values. The brighter a pixel the nearer it is assumed to be to the viewer. The resolution of the produced SIRDS is equivalent to the resolution of the depth image.

In the implemented module a random texture or a predefined texture image can be chosen. Besides there are two control variables to interactively modify the DPI (dots per inch - resolution of the used monitor to be able to specify eye distance E resolution independently) and the variable μ (see section 2).

The predefined AVS module *geometry_viewer* is used to produce an interactive animation. It is capable to produce a grey depth image of a 3D scene, which can be loaded with the *read_geometry* module, by, e.g., using the z-buffer technique with depth cueing as rendering algorithm. The object may be interactivly rotated and translated. The

depth image has to be provided to the *sis* module, which computes a SIRDS. This image is viewed with a *display_image* module. Another *read_image* module can be used to provide the optional texture image. Without an explicitly defined texture image a random texture is used. Figure 3 shows the entire network.

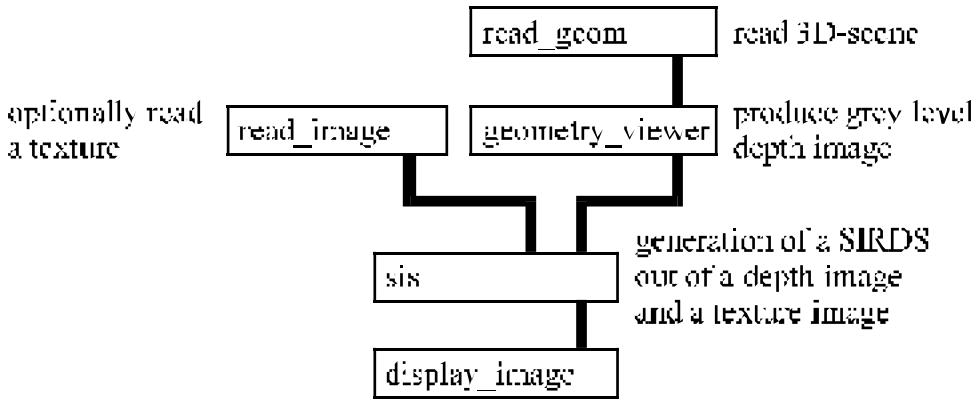

Fig. 3. AVS network to generate a SIRDS.

With this network experiments with interactive animations were made by using the functionality of the *geometry_viewer* module. A serious problem with an interactive application is performance. Although graphic workstations were used (SGI Indigo) some problems occured. Both the *geometry_viewer* module and the SIS module are fast enough, but the transmission of the data between the modules is sometimes too slow. Therefore it may happen that, doing fast changes in the scene, only incomplete depth information is represented in the produced SIRDS.

An interesting animation results from moving an object in a SIRDS with a fixed texture, as in this case only the horizontal lines where the object is depicted differ from image to image. Therefore it looks like the object is moved beneath a table-cloth. Another interesting change results from modifying the parameter μ. Making μ greater the depth of the scene increases, but the image is not so easy to perceive.

7 Experimental autostereograms

There are two research directions where experiments with autostereograms have been done. On one hand the consequences of changing texture colors and on the other hand a fusion of two distinct 3D scenes were investigated.

7.1 Changing colors

The main problem with autostereograms is that the colors of the texture (the image, which can be seen without looking at the third dimension) can be influenced in a small strip only. Because of the dependency chains this strip is repeated more or less distorted over the whole picture.

It would be a nice effect, if the colors of the 2D texture image could be influenced (i.e., dye one area blue and another red). With this effect an independent 2D picture could be incorporated into the autostereogram. The problem is that two corresponding pixels must have the same color, otherwise they cannot be recognized as corresponding pixels. Therefore a solution has to be found to modify the chains of color dependencies. The idea is to reduce the colors of the 2D texture image to only two values, namely bright (e.g., white) and dark (e.g., black). Thereby a SIRMDS is generated. The brain knows to put two corresponding bright or dark pixels on top of each other. Now the colors of the bright pixels can be changed slightly according to the colors of the incorporated 2D picture. It has to be assured that this change must not become too great, because it is difficult for the brain to superimpose two colors which are too different. The most

influence on this ´difference´ is given by the hue value (colors are specified in the HLS color model). Therefore the hue value of two corresponding pixels should not differ too much (e.g., white and yellow).

With this method the colors of the texture of a SIRMDS can be modified in a way that a two-dimensional image is shown. Such a picture is given in Figure 5. Into the 2D texture of this SIRMDS the letters "SIS" are included.

7.2 SIRDS with holes

Another interesting experiment is to merge two distinct 3D scenes into one SIRDS. One possibility to do this is to generate a SIRDS with holes. The idea is to alternate the depth information depending on the coordinates. The whole picture is split up into small squares like a chess board. Then the white squares would show the depth information of the first scene and the black squares would show the depth information of the second scene. In Figure 4 the scheme of the merging is shown.

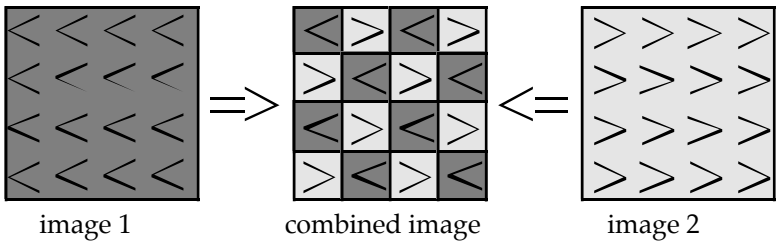

Fig. 4. Scheme of SIRDS with holes.

With this method two independent scenes could be shown simultaneously. The problem is to choose an appropriate size of the holes (the square length can be measured in pixels). If the holes are too small (e.g., 12 pixel with a monitor resolution of 72 dots per inch) then the depth information is very difficult to recognize. If the holes are too big (e.g., 30 pixel) there is too much information of one image shown in those squares where the information of the other image is lost. The chess-board partitioning is thus clearly recognizable.

In Figure 7 a SIRDS with holes is shown where the length of the square-edges is 18 pixel. The whole image has a size of 200x200 pixel. Experiments have shown that the square length of 18 pixel with a monitor resolution of 72 dots per inch is an appropriate size for individual holes.

7.3 Overlapping SIRDS

Another possibility to merge two SIRDS is to overlap them. To do this it is important that the brain can filter which pixel belongs to which 3D scene. The idea is to take two SIRMDS and dye them with different colors. These colors should be easy to seperate. Experiments have shown that the hue value (in the HSL color model) has to differ largely. The colors red and blue, for example, have shown to be appropriate. The background is dependent on the output media. When a monitor is used it should be black and when the autostereogram is printed on a sheet of paper the background color should be white.

After producing the two SIRMDS they are both projected pixel by pixel onto one picture. If the pixels from both SIRMDS have the background color, the resulting pixel gets also the background color. If one of the pixels is red (or blue) and the other one has the background color, the resulting pixel is colored red (or blue). If both pixels are colored red and blue the resulting color is chosen randomly as being either red or blue. Such collisions can be reduced if the percentage of the red (or blue) pixels with respect to the background pixels is low (e.g., 30% to 70%). This fact can be achieved by coloring more dependency chains in the two original SIRMDS in the background color than in red (or blue).

If the overlapping SIRDS is produced with a ratio between the number of foreground and background pixels as given above, the brain can differ between the two 3D scenes. One gets the impression of seeing two transparent 3D scenes. An example is shown in Figure 9. Overlapping SIRDS are somewhat difficult to see, but they produce quite interesting results.

8 Conclusion

In this paper a detailed classification of autostereograms has been given and experiments with animated SIRDS were made. Moreover results of some experiments with autostereograms are discussed. SIRDS with holes and overlaping SIRDS can merge two different 3D scenes, and a method was investigated to modify the colors of textures of a SIRDS. More details can be found in [Tonn95].

Autostereograms are an interesting topic in computer graphics. Because they convey a three dimensional impression of a scene in a single image, autereograms produce fascinating and aesthetically pleasing images.

9 References

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10 Images

The images can also be found at http://www.cg.tuwien.ac.at/research/autostereograms/index.xhtml

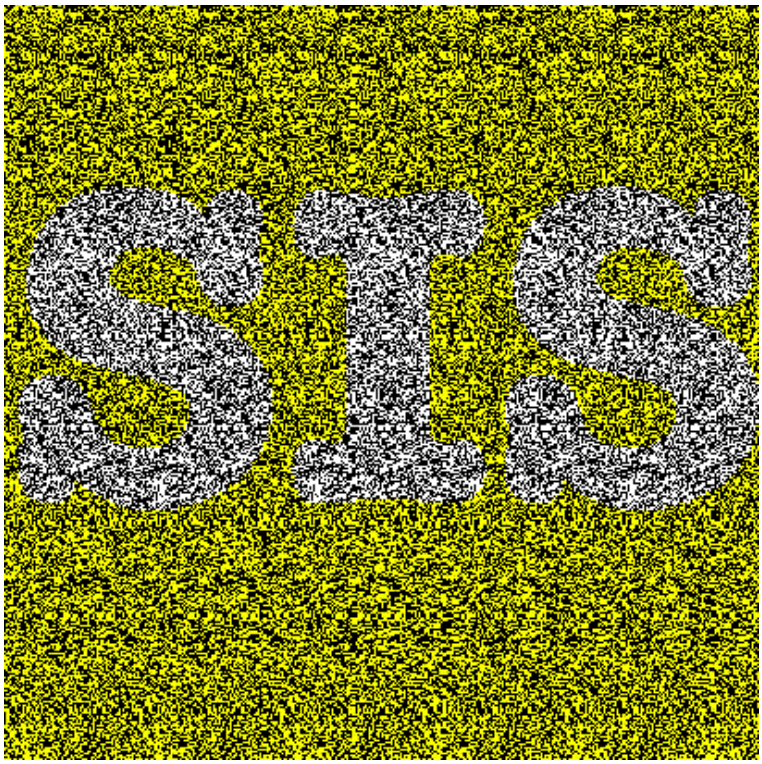

Fig. 5. Changing colors (for depth image see Fig. 6) (see Appendix).

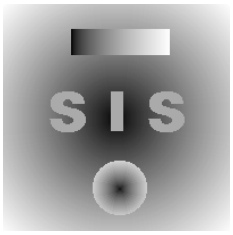

Fig. 6. 3D scene.

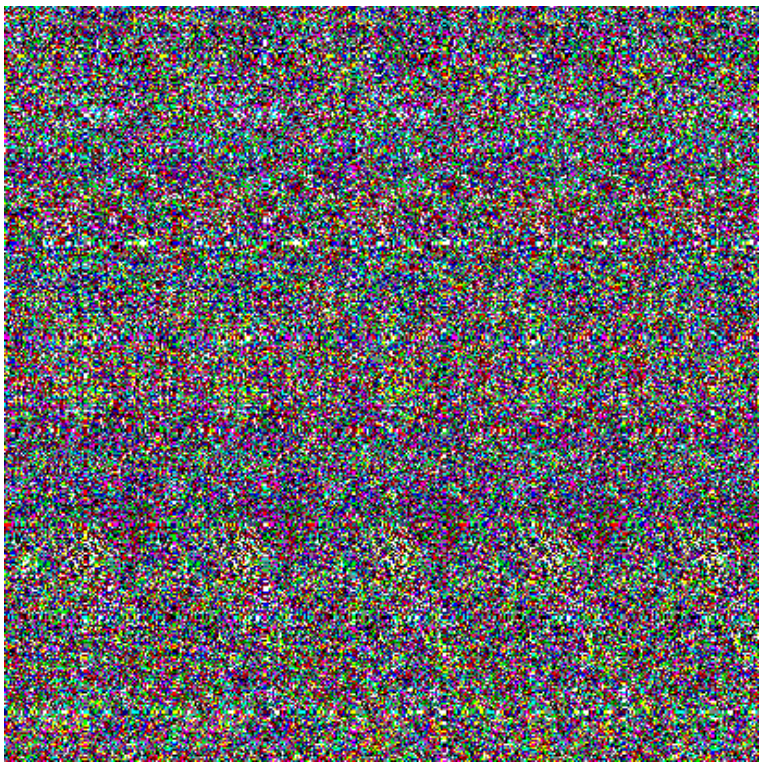

Fig. 7. SIRDS with holes (for depth image see Fig. 8) (see Appendix).

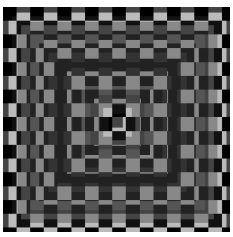

Fig. 8. 3D scene.

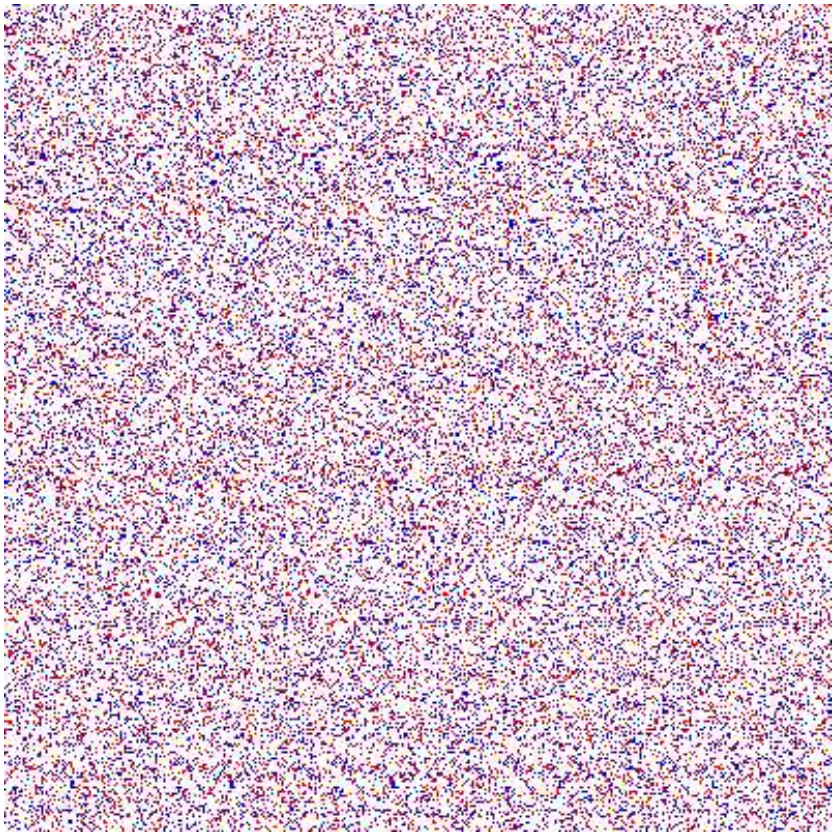

Fig. 9. Overlapping SIRDS (images of Fig. 10, 11) (see Appendix).

Fig. 10. scene 1.

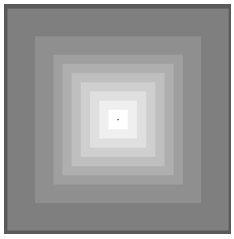

Fig. 11. scene 2.