A Real-time Three-dimensional Graphics Display

By A. H. Sale* and A. G. Bromley †

The visible surface problem for three dimensional objects is examined from a global point of view in which planar surfaces derived from convex three dimensional objects are regarded as the natural display elements. By retaining global information on surface and object relationships it is possible to considerably simplify the resolution of visible surfaces for a large class of realistic objects. Implementation of this approach suggests a display in which surfaces written to the display device can overlay and obscure previous picture information in the manner of oil painting. A display system is proposed in which this is implemented by a large buffer memory which holds a complete point-by point description of the picture in low cost MOS shift-registers. By combining new data to be entered into the memory in a variety of ways with the data already present, it is possible to considerably enhance the display's capabilities. The buffer memory also allows an easy match of the display system to conventional (TV) video equipment.

KEY WORDS AND PHRASES

real-time display, real-time graphics, three-dimensional graphics, visible surface problem, picture processing, picture buffer memory, display buffer, MOS memory, TV display, TV video.

CR CATEGORIES

3.80, 6.22, 6.34, 6.35.

1. INTRODUCTION

The display of reasonably realistic representations of three dimensional objects and scenes has been the subject of considerable interest in recent years. Much work in this area has been dominated by consideration of the so-called visible-surface problem: the determination of which surfaces of an object are wholly visible, completely invisible, or partially visible; and the partitioning of surfaces in the last class so that the components fall into either of the first two categories. Several algorithms are known which have been successfully applied to static pictures (Romney 1970, Warnock 1969); the problem is now in finding methods which are sufficiently time-efficient to permit real-time display of realistic moving objects. The most successful work in this direction to date has been at the University of Utah (Watkins 1970). A number of other problems are now also assuming considerable importance.

The best current visible-surface algorithms are limited to planar surfaces: generally triangles and quadrilaterals. However curved surfaces are rather frequent in real life objects – aircraft structures are a common example in the literature. The usual approach in such cases is to approximate each curved surface by a number of small planar fragments so that efficient visible surface algorithms can be applied. The resulting displays appear quite unrealistic. There have been some attempts to represent curved surfaces by fragments of higher order surfaces than planes (Jones 1971, Woon 1970), but the success of these ventures has fallen well short of that necessary for use in a real-time display.

Gouraud (1971) has demonstrated that the appearance of curved objects can be markedly improved if the surface is approximated by planar fragments which are not shaded uniformly but rather by a linear interpolation of the average visual intensity at the vertices of the fragments. This removes discontinuities in the visual intensity between the approximating planar fragments. Although there are discontinuities in the derivative, the visual effect of these is minor. The success of Gouraud's work is such that shading should be considered an essential facility in any new display system.

Another simplification commonly made is to assume that the surfaces are matt diffusers illuminated from the eye-point of the observer. This considerably simplifies the display problems by eliminating specular reflections of one surface in another, shadows, and the additive effects of many light sources. However the displayed objects as a consequence appear rather dead and metallic. Some work has been done towards removing these limitations (Bouknight and Kelly 1970) but the added complexities are not yet commonly regarded as justified. Similarly contributions to luminous flux on a surface due to diffuse reflections from other surfaces are also ignored. The effects on monochrome representations are minor but the resulting colour shifts can be quite noticeable.

In addition to these visual simplifications certain physical simplifications are commonly made. Deformable objects (balloons, cloth), interpenetrating objects (knife into butter) and refractive problems (lenses, prisms), are excluded. However assemblages of objects, such as a flight of aircraft, or a nut on a bolt, are allowed. Many of these are best considered as problems in the assembly of objects and scenes rather than as problems of display.

The work described in this paper is based on two additional convictions of the authors:

(i) that previously proposed methods of displaying moving objects did not take enough account of readily recognisable geometric and topological relations between surfaces, and

(ii) that there seemed to be considerable value in a single memory to hold a bit-by-bit representation of a picture as it is generated, both to allow manipulation of the picture as it is generated, and to ease problems of interfacing to a variety of

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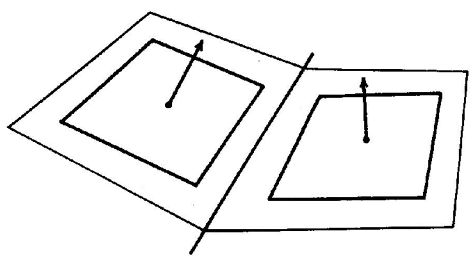

Figure 1 Circumstances in which two surfaces are positioned such that neither can ever obscure part of the other.

displays including conventional (TV) video equipment.

These ideas are developed more fully in the following sections, leading to a design for a proposed real-time display.

2. GLOBAL ASPECTS OF PICTURE PROCESSING

Consider the problem of displaying a cube described by its six bounding surfaces (planar quadrilaterals). At least three of these surfaces are invisible at any one time as they face away from the observer, and a maximum of five of the surfaces may be invisible for this reason. Such surfaces can be eliminated from consideration immediately if each surface has a definite 'face' possibly indicated by labelling the vertices always in a counterclockwise sense when the surface is viewed from the outside (Gouraud 1971). Such a simplification is not possible if apparently hollow objects are allowed so that a surface may be seen from the inside. This possibility is eliminated by our restriction to the solid objects as all real objects have a finite thickness: the inner and outer surfaces are distinct.

This mechanism is the only one by which a surface of an isolated cube can be made invisible. There is a strict non-interference of faces of a cube so that no surface can ever obscure part of another. This is a powerful notion and can clearly be generalized to all convex objects. For non-convex objects two surfaces can never obscure part of each other if, when viewed from the direction of the common 'face' of both, they lie on opposite sides of the line of intersection of the planes of the surfaces. Figure 1 illustrates this.

A more limited form of non-interference is shown in Figure 2. The outer surfaces of a cube can obscure the inner surfaces of a hole through the cube but not conversely. A similar situation occurs with many re-entrant objects. (See Figure 8.)

These observations suggest that for any object or set of objects it is possible, for a given viewpoint, to do a 'depth sort' of the visible surfaces to rank them so that any surface which obscures part of another appears after it in the ranking. If this is so it is possible to display the surfaces in the ranked order to give a correct rendition of the scene, provided later surfaces obscure or overlay earlier ones in the manner of (say) oil painting. This overlay idea is the central concept of the display to be described. An underlay type of display is also possible if the surfaces are displayed in a reverse ranked order.

The non-interference relations described above are of considerable aid in carrying out a depth sort of visible surfaces. However Figure 3 demonstrates an object in which either of two surfaces may obscure part of the other depending on the viewpoint. There is no non-interference relation, independent of the viewpoint, of the type described above. The depth sort may also be relatively inefficient as the set of visible surfaces is only partially ordered; two surfaces may appear disjoint and their depth relation can then only be determined by examining any surfaces which overlay one but underlay the other.

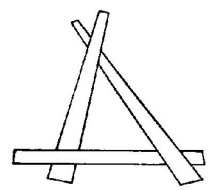

Figure 4 No unique depth ranking of the surfaces, A,B,C is possible unless one of the surfaces is partitioned.

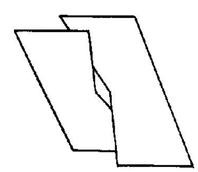

Figure 5 A unique depth ranking may not be possible unless a restriction is made to convex planar surfaces.

The overlay approach may breakdown completely in some circumstances. Each of the three surfaces in Figure 4 obscures part of another in a cyclic manner so that no unique depth ranking is possible. This problem can only be resolved by partitioning one of the surfaces involved, but this is scarcely a task for the display itself. Fortunately such situations are exceedingly rare in practice. A more common problem can arise with re-entrant surfaces as shown in Figure 5. This particular difficulty is easily resolved by restricting object descriptions to convex planar surfaces only.

These ideas can be extended to an assembly of objects in a fairly direct manner. Consider the problem of displaying a pair of cubes as in Figure 6.

If none of the techniques described above are used 66 comparisons of pairs of surfaces are necessary during the display process. By eliminating invisible rear surfaces this is

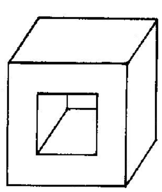

Figure 2 The outer surfaces of the cube may obscure the inner surfaces of the hole but not conversely.

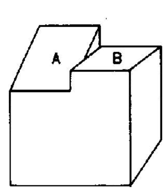

Figure 3 A pair of surfaces either of which may obscure part of the other depending on the view point.

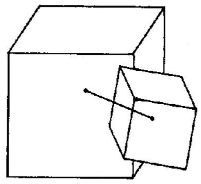

Figure 6 A pair of cubes illustrating a number of techniques for the display of an assemblage of objects.

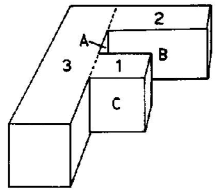

Figure 7 An example of the use of linear separation by abutment planes in resolving complex objects.

reduced to 15. Eliminating the comparison of non-interfering surfaces of each separate cube reduces this to 9. If now we note that the cubes are non-interpenetrating (since each is solid) the first pair of overlapping surfaces on different cubes yields all necessary information; one cube is displayed before the other, and the 9 comparisons are necessary only if the cubes are completely visually disjoint. A further reduction may be had if the surfaces against which the line joining the centres of the cubes is projected are compared first. This heuristic will resolve overlapping cubes in an average of about 2 comparisons, although the worst case (for visually disjoint cubes) still require 9 comparisons. These techniques yield about an order of magnitude work improvement in the display of two cubes and can be generalised to other pairs of convex objects with similar gains.

An even simpler method for resolving the visual relationship of two non-interpenetrating convex objects exists. In any configuration there exists at least one plane which linearly separates the two objects; one object lies entirely on one side of the plane whilst the second lies entirely on the other side. Indeed if the objects are bounded by planar surfaces at least one surface of one object will be such a plane. The object on the same side of the plane as the observer can only be disjoint from or overlap the other. If the observer is on the plane the objects are visually disjoint. An examination of the 'face' of a single plane can therefore resolve the depth relations of any two convex objects. Unfortunately the plane changes as the objects move relative to one another; but this problem may possess a simple solution at the assembly stage of the display process when the dynamics of the system are known.

An important special case arises with objects formed from convex objects permanently abutted, such as the components of the letter F in Figure 7. The surface A of block 3 serves to define the visual relation of block 3 to blocks 1 and 2, while surface B (or indeed C) defines the relation of blocks 1 and 2. An examination of the 'face' of A and B is sufficient to completely determine the order for display of surfaces of this object. Excellent examples of the use of this technique can be found in the display of aircraft structures; natural linear separations exist between the fuselage and the tail, tailplane, wings, canopy, etc. The structure in Figure 8 is resolved upon the examination of just two planes. One plane between the wing and the engine indicates whether the wing and engine support can overlap the engine itself, or vice versa. The 'face' of the plane of the engine support indicates the sequence for drawing the two halves of the wing and the engine support; either a, b, c or c, b, a in the figure. The concave curve of intersection of the wing and the engine support thus poses no problems. The air intake also poses no problem, the surfaces are always displayed in the sequence a, b, c shown, excluding rear facing surfaces of course.

More difficult problems exist, particularly when an object enters a cavity in another, for example the rod and washer in Figure 9. One method which can be used in such cases is to divide the concave object into a number of small convex parts. A more efficient approach would be to dissect the concave object at the tangent points to the line of observation as shown X - Y, but this is scarcely a function for the display process. At worst a surface by surface examination of the objects will suffice.

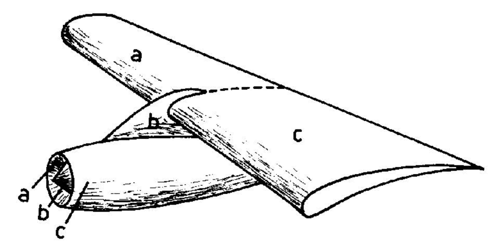

Figure 8 An application of the method of planar separation to a realistic combination of concave and convex objects.

The discussion above demonstrates the advantages for a high speed display of treating surfaces as natural elements for the description of objects and of preserving a substantial amount of information about objects and their relationships. Although this approach assigns considerable responsibility to the display user to generate, maintain, and utilise such global information the authors believe that a substantial improvement in the performance of high speed graphics systems can result. Other authors have described methods by which global concepts can be effectively applied to a number of other graphic tasks (Jones 1971, Matsushita 1972).

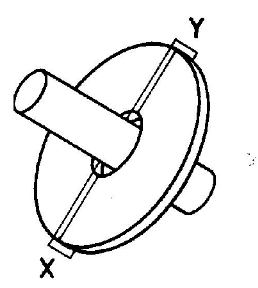

Figure 9 Difficulties can arise in the display of objects with cavities into which other objects may penetrate.

3. A PICTURE BUFFERED DISPLAY

The preceding discussion indicates the need for a display whose natural data type is shaded planar surfaces: triangles and possibly quadrilaterals.

An early decision was made that the display device itself should be a conventional video monitor. This has a number of advantages: development costs are zero; the units are low cost making it feasible to carry spares and provide slave displays; colour displays are readily available; and standard recorders, mixers, and editing devices are readily available. However the devices are of relatively low precision and picture quality.

A significant feature of video is that the display is raster scanned. Although this is an efficient method for shading extended areas it does not seem effective to generate directly in this one dimensional form picture elements which are naturally described in two and three dimensions. Although displays have been designed to use this approach (Watkins 1970) they are hampered by the high data rate in a TV picture scan and by catastrophic breakdown of display capability beyond a modest picture complexity.

A natural solution to this difficulty is to provide a buffer memory to hold a bit-by-bit representation of the picture (Newell, Newell and Sancha 1972). The display can generate and manipulate picture elements in this memory in any manner suited to its operations whilst the output for the monitor can be extracted from the memory in any desired format. A random access memory is both too slow and too expensive for this purpose. A MOS shift register memory is however much cheaper, and although the possible modes of access to picture information are restricted, the possibility of high simultaneity confers many advantages on the display. This apparently primitive solution was therefore adopted.

Consider the picture memory to be composed of a rectangular array of points, making up a picture. At each point some 10-15 bits of intensity and colour information may be needed. Imagine then that for each vertical column of points we provide a set of 10-15 MOS shift registers so that the total information regarding one point of the picture is available at any one instant at the ends of the shift registers. Imagine further that we replicate this assembly for every column of points in the picture (so that the information corresponding to all points in a single horizontal row is simultaneously accessible). If all these registers are circulated in synchronism at approximately the TV line scan rate of 15.625 kHz*, then during one cycle all points of the picture will have been made available for modification, and consequently it should be possible to enter at least one picture element (shaded planar surface) approximately every 64 μsec. This complete memory is referred to as the picture 'barrel', a name which evokes a fairly accurate image of its operation.

Although it is not necessary to constrain the rotation of the picture barrel to TV scan rates during the picture generation let us suppose that this is so in order to develop performance measures for the display. 512 lines of picture is reasonable after allowance is made for the frame fly back time. 512 points per line would utilise 60-70% of the width of the TV screen and provide a square picture in the best resolved part of the screen. Points in the picture are thus scanned at 10-12 MHz during the active part of the line scan or at an average rate of 8 MHz after allowance for line scan flyback. If picture elements are to be entered into the memory at line scan rates (64 μsec each) the MOS shift registeres must attain a shift rate of 8-12 MHz and the display generator is constrained to update each complete horizontal line of a picture within 80-120 nsec. This is just possible for linearly shaded planar surfaces with current (ECL) technology. With this display it appears practical to generate pictures with perhaps 500 visible surfaces at a repetition rate of 15-20 frames per sec. It is interesting to remark that the maximum data input rate to the picture memory (for example when blanking the screen) is near 100,000 megabits/sec.

It is necessary to decouple the display of the contents of the memory from the generation of the picture since writing one picture element into the memory may overlay previous picture information. Thus the picture information in the memory is appropriate for display only when the generation of the picture is complete, and it is necessary to interleave periods when the picture is generated with periods when it is displayed. The actual display must take a complete frame time but need not be synchronised to conventional frame boundaries. Consequently as the picture complexity increases the display frame rate decreases so there is a gradual deterioration of the display. For very complex pictures the intensity flicker caused by the blanking of the display would become a problem but could be removed by a video disc or similar buffer between the picture memory and the display monitor.

There are several significant practical advantages in this decoupling of the generation and display of pictures. During picture generation the shift rate of the MOS registers may be reduced to ease speed constraints on the picture element generation hardware. The barrel may even be stopped completely for brief periods to allow a synchronous set-up of the picture generation hardware and thus make possible a higher overall generation rate. While displaying the picture the barrel need only rotate at frame rates rather than line scan rates. This would reduce the duty cycle of the MOS registers and yield significant advantages in power consumption, heat dissipation and reliability of the picture memory.

4. PICTURE PROCESSING IN A BARREL MEMORY

Each vertical line of the picture is represented in the barrel memory by a number of MOS shift registers, one for each bit of information at every point in the picture, as indicated in Figure 10. The input logic normally serves to recirculate the contents of each line of the picture. However new information can be added from the picture generation hardware to modify or replace the current information at any points. The power of the display is in large part a function of the characteristics of the input logic.

Two constraints must be observed in the design of the input logic. Since the input logic must be replicated for each vertical line of the picture, approximately 512 times, it must be as simple and economical as possible. The rate at which a picture can be generated is a direct function of the shift rate of the barrel registers, 8-12 MHz being necessary to generate a picture element within a video line scan time of 64 μsec. The delay in the input logic can therefore be no more than 80-120 nsec less the set up time of the MOS shift registers. These conflicting requirements pose severe design constraints.

* *All video data refer to the Australian 625 line PAL standard.*

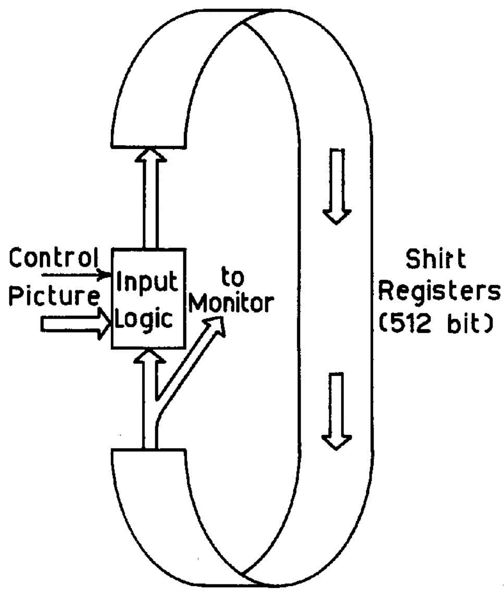

Figure 10 One vertical line of the picture as stored in the barrel.

Uniformly Shaded Areas

Uniformly shaded areas are a basic picture element for the display of three dimensional objects as well as animation board graphics, etc. Suppose we wish to display a triangle. A horizontal section of this in the picture space is a single line segment. The coordinates of the end points of this line segment are interpolated by line generators to the resolution accuracy of the display raster from the coordinates of the verticles of the triangle. The end coordinates are applied to a fast ECL carry look ahead network which generates a control signal output to all vertical lines within the line segment intercept of the triangle. The input logic, which normally simply recirculates the line contents, gates instead the constant intensity and colour information for the triangle into the selected lines. Any previous picture information is thus overlayed or by the newly entered information. Details of the logic for this and other functions described in this section are discussed elsewhere (Bromley 1973).

This type of area generator could be generalised to any convex surfaces without changing the input logic to each recirculating vertical picture line. However there seems little value in generating polygons other than triangles and quadrilaterals. It may be possible to display areas with non-linear bounding curves by adding higher order differences in the line generators. However this approach has not been explored in depth.

Linearly Shaded Areas

To smoothly shade a three dimensional object in the manner discussed by Gouraud it is necessary to linearly interpolate the intensity of an interior point of an area from the presumed intensities at the vertices. This should only be attempted for triangular areas as there is no guarantee that the vertices of more complex areas are coplanar in intensity space.

The input logic for each vertical line that is covered by the triangle is preset with the intensity computed along the first horizontal line to intersect the triangle. The line generator logic is used for this purpose as the intensity is a linear function of the horizontal coordinate. As the barrel rotates each line updates the current intensity using the intensity gradient in the vertical direction. The control lines are activated for all points within the triangle using the mechanism described for uniformly shaded areas but the current interpolated intensity for that line is inserted in the memory. Linear shading is slower than uniform shading because of the time required to preset the intensity in each line input logic.

Picture Masking

An effective device for making the barrel a more powerful picture processor is to add a single extra plane (one bit for each point in the picture) and contriving that no new picture information is entered at any point if the corresponding mask bit is set. If the mask bit is automatically set whenever picture information is added at a point we can generate pictures by underlaying; entering the nearest surface first and then adding those partially obscured by it. Alternatively photomontages or inset enlargements of portions of a picture can be made by masking all but a portion of the memory at a time so any picture elements extending beyond the unmasked area are clipped.

Direct Depth Discrimination

Direct depth discrimination of surfaces is possible if sufficient planes are added to the barrel to maintain the depth coordinate at each point in the picture of the currently visible surface. As each surface is entered into the picture its visual depth coordinate is generated using the same mechanism as linear intensity shading. If the depth coordinate at any point is less than that of the currently visible surface at that point the new depth coordinate is entered and the picture is updated.

Although this technique can correctly handle any combination of inter-twined and intersecting surfaces it is probably too expensive for most applications. The cost of the barrel is doubled or more by the addition of new memory planes and complication of the input logic.

Filters

The effect of a transmission filter lying across part of a picture is quite easily introduced. The control lines are activated for those parts of the picture covered by the filter. The input logic for those lines take the present intensity and colour information for that point of the picture and, using the characteristics of the filter, computes the new intensity and colour information for entry into the barrel. Although this is not complex the hardware cost is probably justified only in rare cases.

5. CONCLUSION

It is apparent that significant performance advantages are made possible by adopting a global approach to picture processing in which shaded planar surfaces and convex three dimensional solids are regarded as the basic picture element.

Based on these ideas a design for a proposed graphics display has been described which has shaded areas as the basic picture element. This device is capable of a comparable picture quality but higher display speed than existing three dimentional displays. It has the considerable advantage that the display of complex pictures results in only a gradual degradation in the picture quality (intensity and movement flicker); thus much more complex pictures can be displayed in real time than is at present possible. The ability to mask and otherwise manipulate portions of a picture during the generation process adds a significant new display capability.

The present (1973) cost of the picture memory is around $A3,000 for each plane of the barrel. Allowing 20% above the memory cost for the barrel input logic, the barrel of a system with 6 bits of intensity, 4 bits each of two chrominance signals at half resolution, and one mask bit per point of the picture would be around $A40,000. On this basis the cost to build a complete display processor would be around $A60,000. This appears competitive with existing three dimensional display systems.

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