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Drebin et al.

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(54) ACHROMATIC LIGHTING IN A GRAPHICS SYSTEM AND METHOD

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(73) Assignee: **Nintendo Co., Ltd.**, Kyoto (JP)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 128 days.

(21) Appl. No.: **09/726,216**

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(51) **Int. Cl.**^{7} **G06T 15/60**

(52) **U.S. Cl.** **345/426**; 345/582; 345/589; 345/520; 345/420

(58) **Field of Search** 345/426, 582, 345/419, 522, 420, 589

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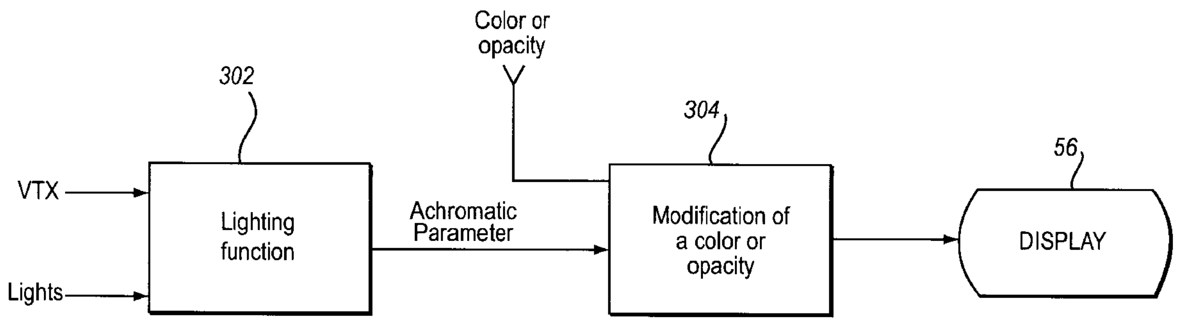
(57) **ABSTRACT**

A graphics system including a custom graphics and audio processor produces exciting 2D and 3D graphics and surround sound. The system includes a graphics and audio processor including a 3D graphics pipeline and an audio digital signal processor. Cartoon lighting and other non-photorealistic effects can be produced by using a lighting calculation to produce a parameter other than color or opacity for use in a later modification of a color or opacity value. In more detail, the example embodiment uses the lighting calculation to generate texture coordinates used in a texture mapping operation. The texture mapping operation allows lighting computation results to select between brush strokes for cartoon lighting and other effects. The resulting dynamic cartoon lighting animation can be performed on a low cost platform such as a home video game system or personal computer.

22 Claims, 24 Drawing Sheets

(1 of 24 Drawing Sheet(s) Filed in Color)



EXAMPLE IMAGE GENERATING PROCESS

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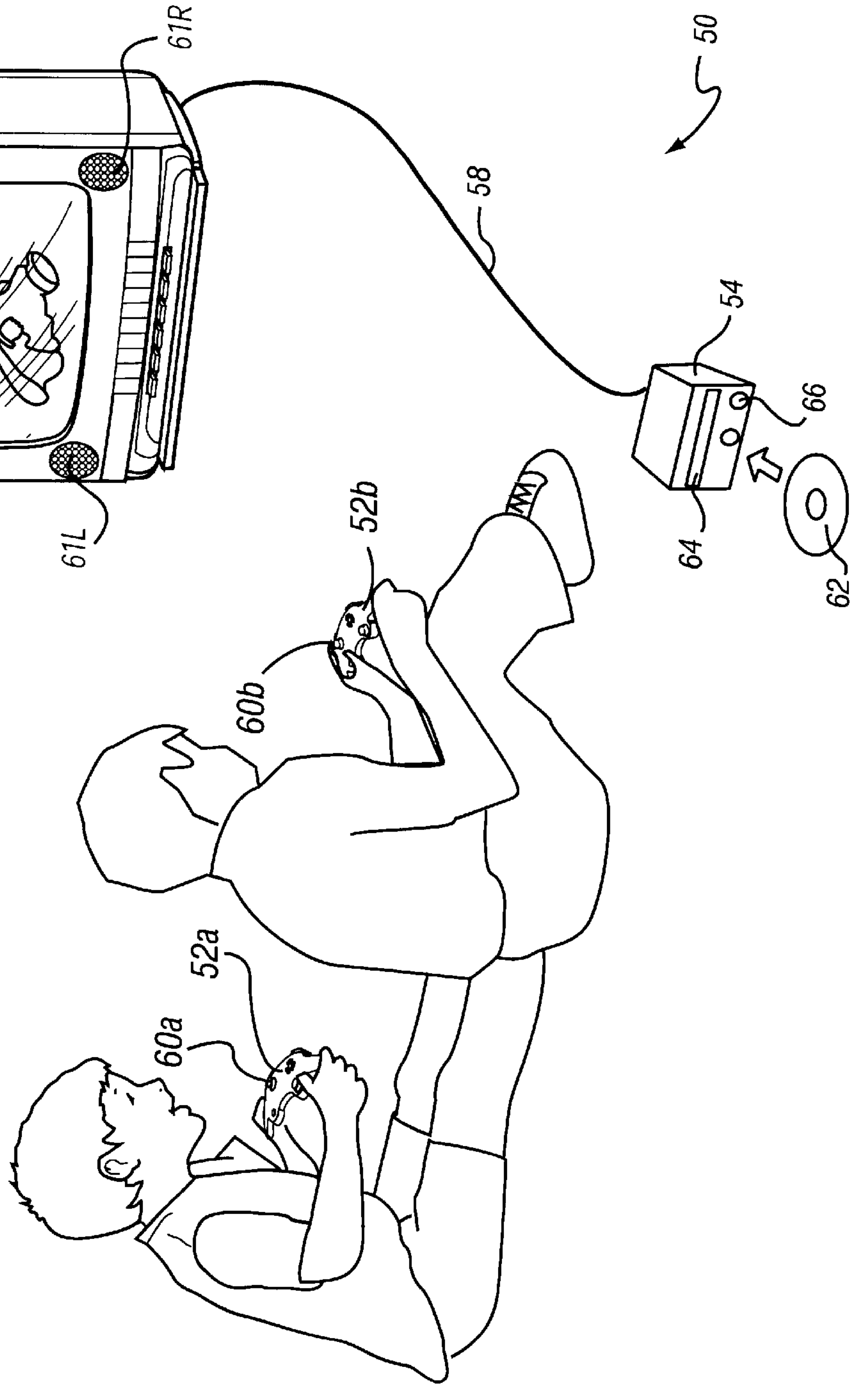
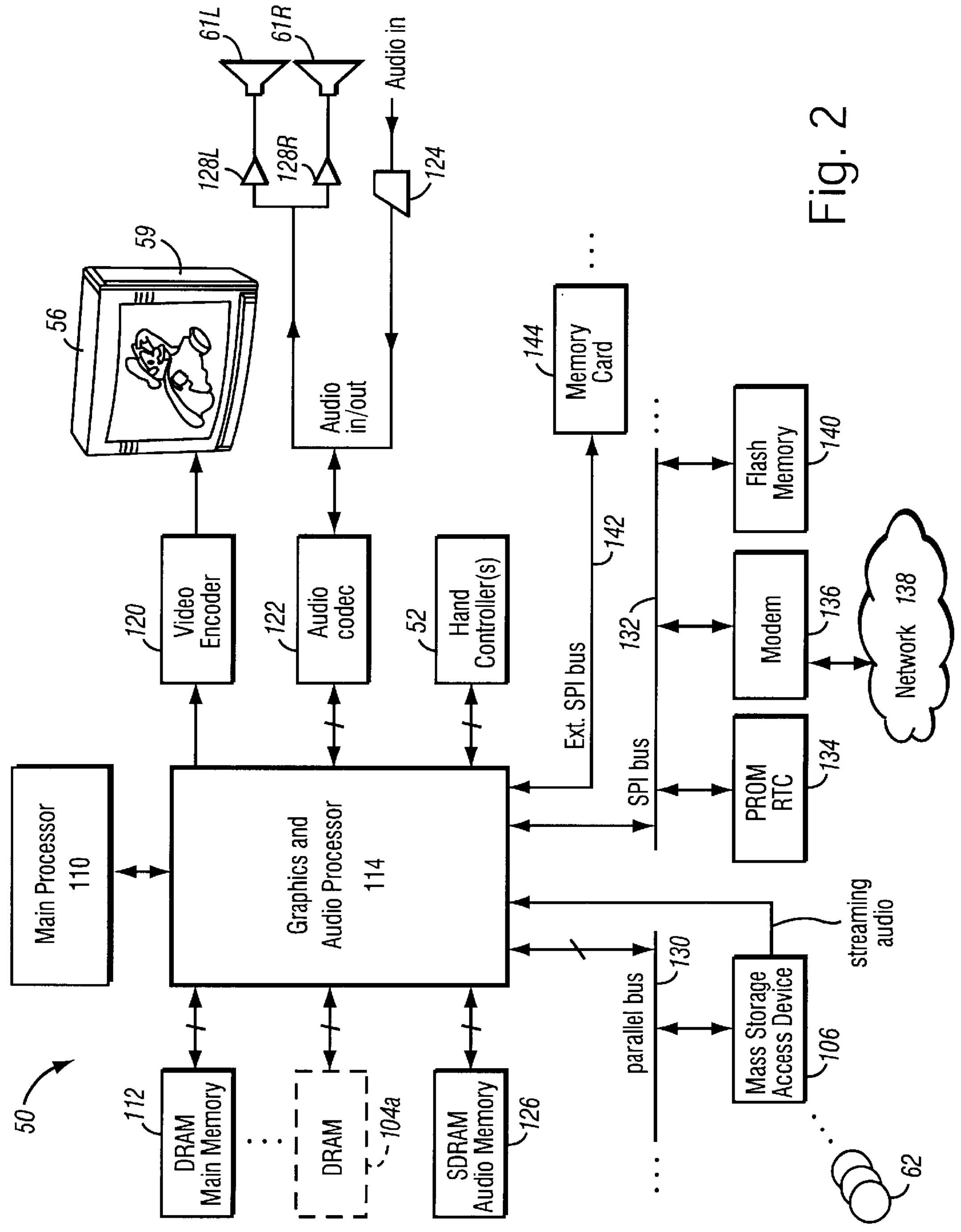
Fig. 1

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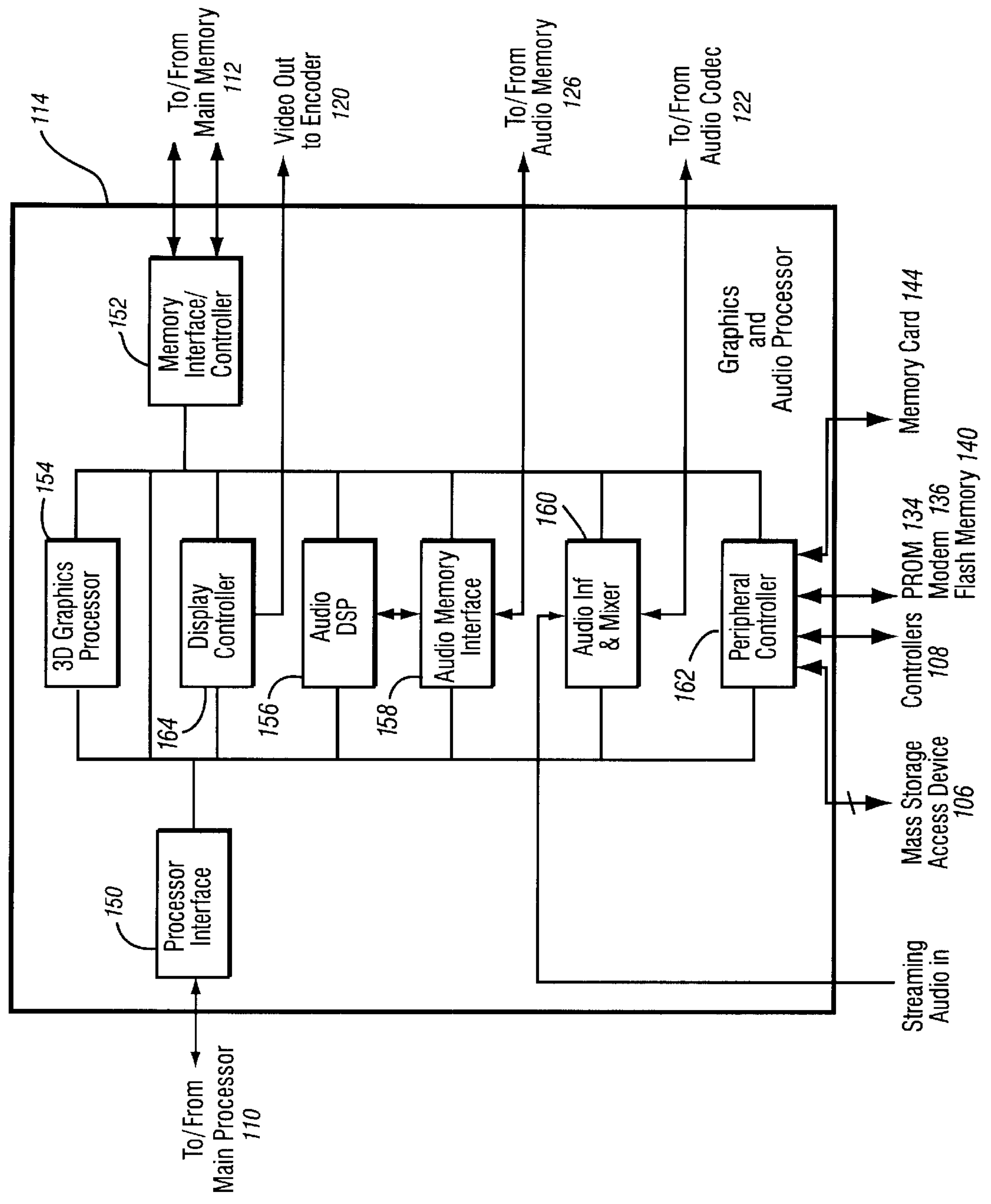
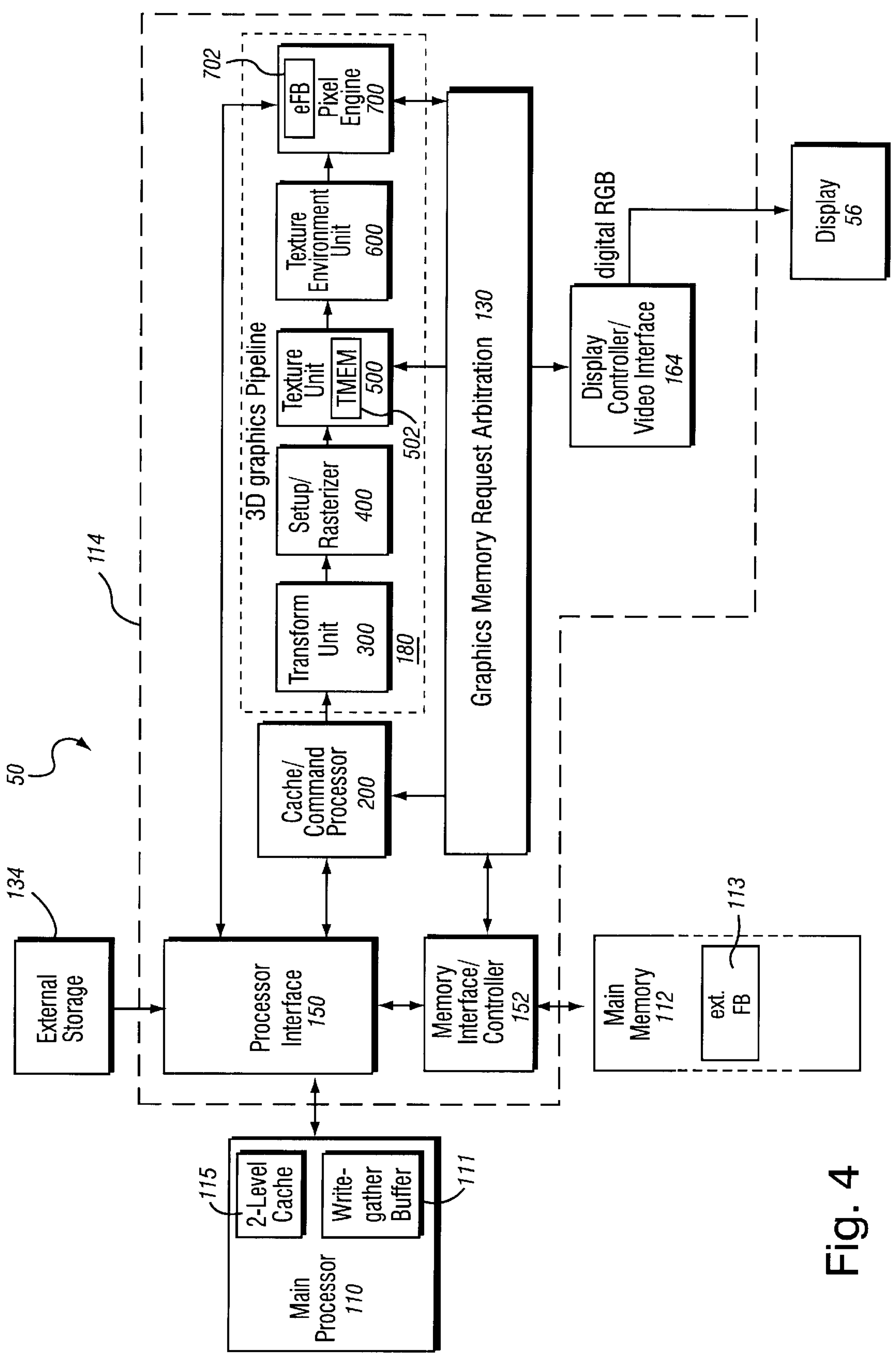
Main Processor 110
Graphics and Audio Processor 114
DRAM Main Memory
112
DRAM
104a
SDRAM Audio Memory
126
Video Encoder
120
Audio codec
122
Hand Controller(s)
52
56
59
Audio in/out
128L
128R
61L
61R
124
Audio in
Ext. SPI bus
142
Memory Card
144
SPI bus
132
PROM RTC
134
Modem
136
Network 138
Flash Memory
140
parallel bus
130
Mass Storage Access Device
106
streaming audio
62

Fig. 2



114
To/From Main Memory 112
Video Out to Encoder 120
To/From Audio Memory 126
To/From Audio Codec 122
152
Memory Interface/ Controller
Graphics and Audio Processor
154
3D Graphics Processor
Display Controller
Audio DSP
Audio Memory Interface
160
Audio Inf & Mixer
Peripheral Controller
164
156
158
162
Memory Card 144
PROM 134
Modem 136
Flash Memory 140
Controllers 108
Mass Storage Access Device 106
150
Processor Interface
Streaming Audio in
To/From Main Processor 110

Fig. 3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114
134
External Storage
Processor Interface 150
Memory Interface/ Controller 152
Main Memory 112
ext. FB
113
Main Processor 110
2-Level Cache
115
Write-gather Buffer
111
Cache/ Command Processor 200
3D graphics Pipeline
Transform Unit 300
180
Setup/ Rasterizer 400
Texture Unit 500
TMEM
502
Texture Environment Unit 600
eFB
702
Pixel Engine 700
Graphics Memory Request Arbitration 130
Display Controller/ Video Interface 164
digital RGB
Display 56

Fig. 4

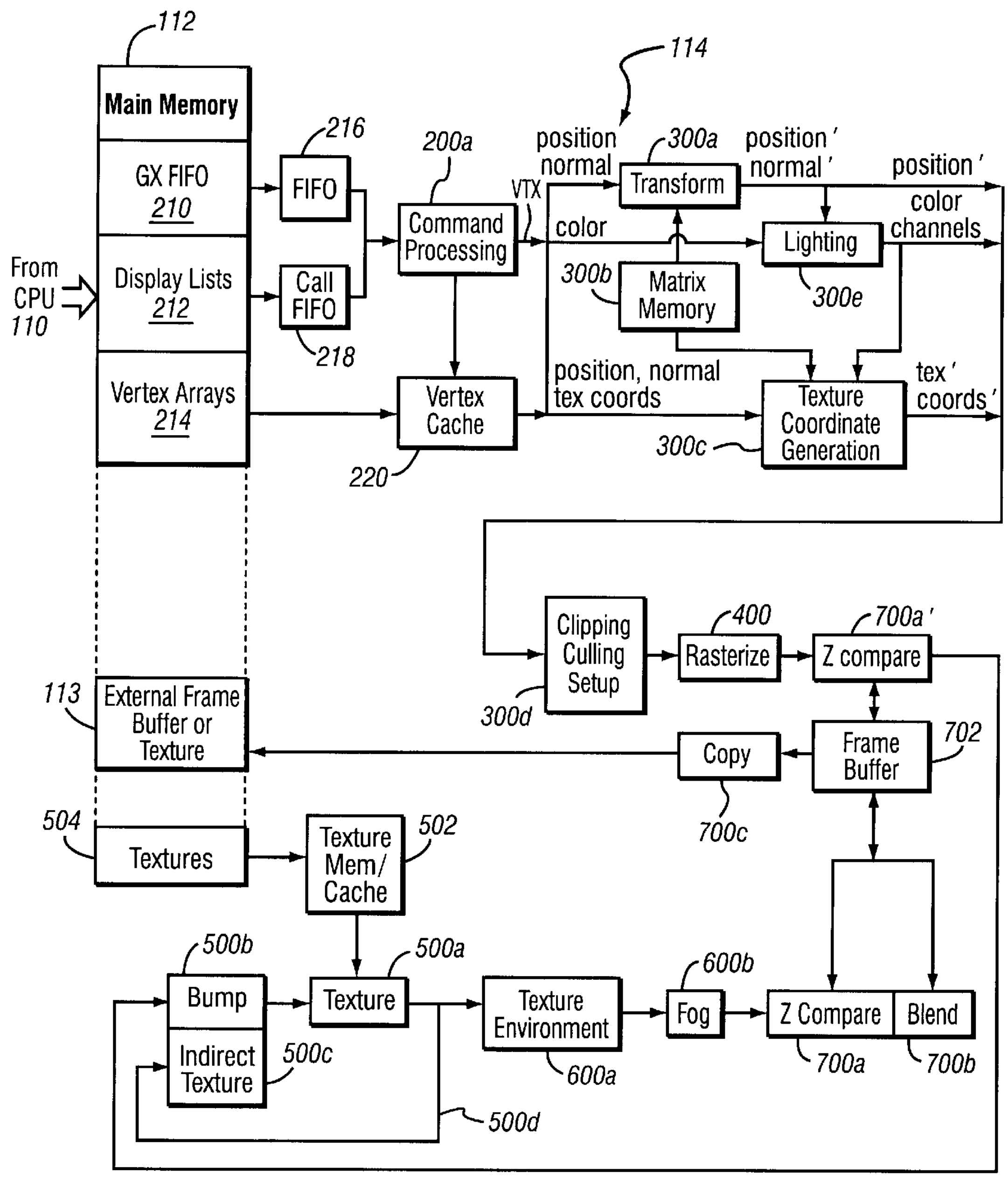


Fig. 5 EXAMPLE GRAPHICS PROCESSOR FLOW

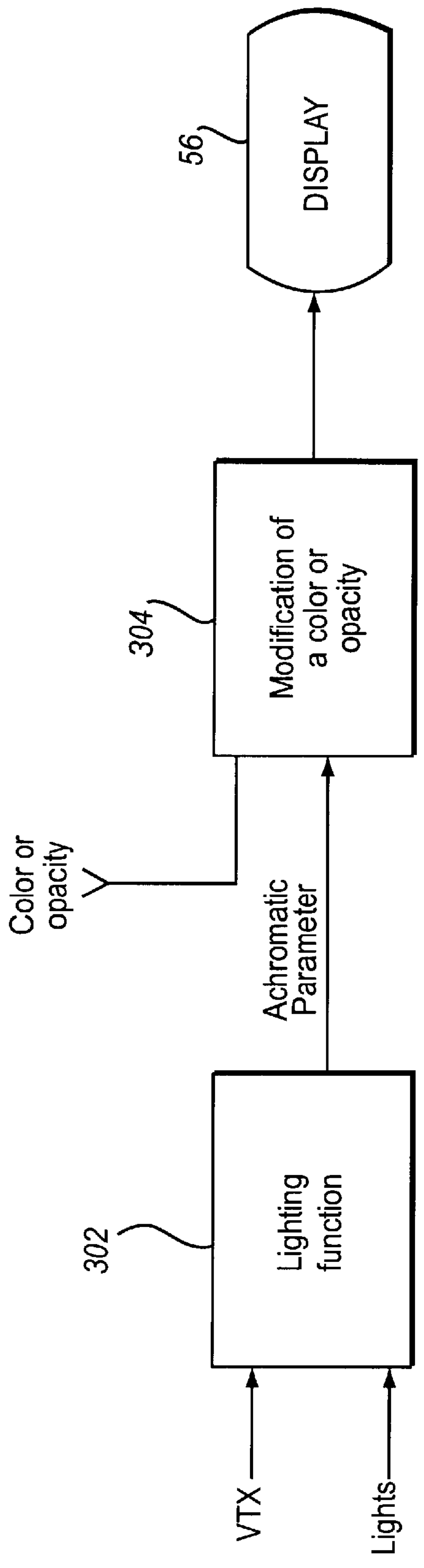


Fig. 6 EXAMPLE IMAGE GENERATING PROCESS

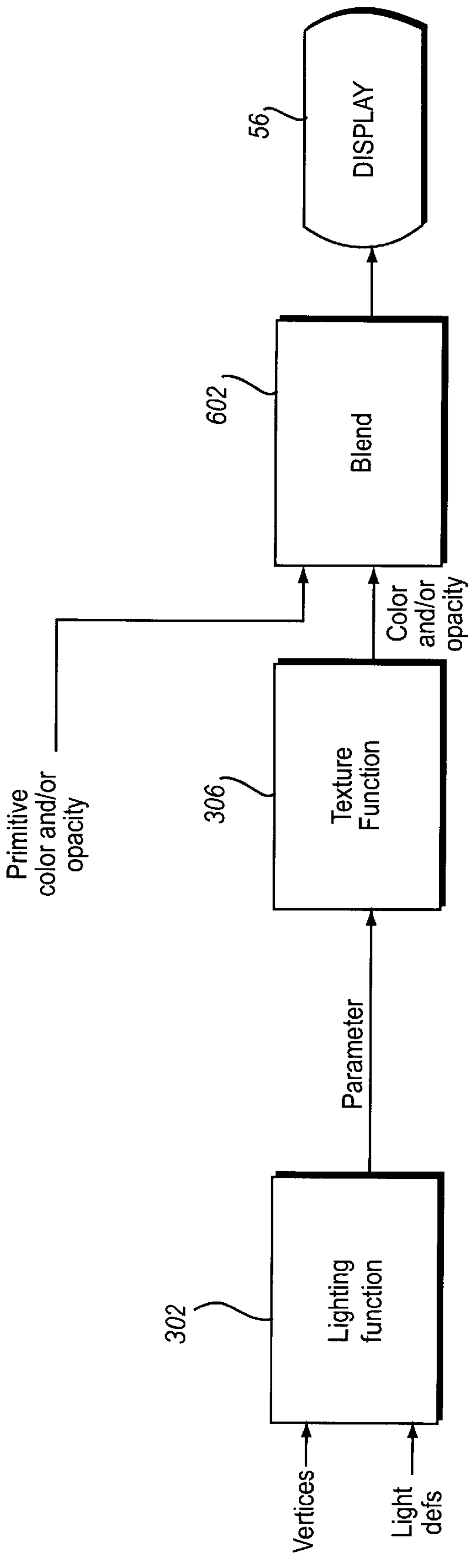


Fig. 7 EXAMPLE TEXTURING PROCESS BASED ON ACHROMATIC LIGHTING PARAMETER

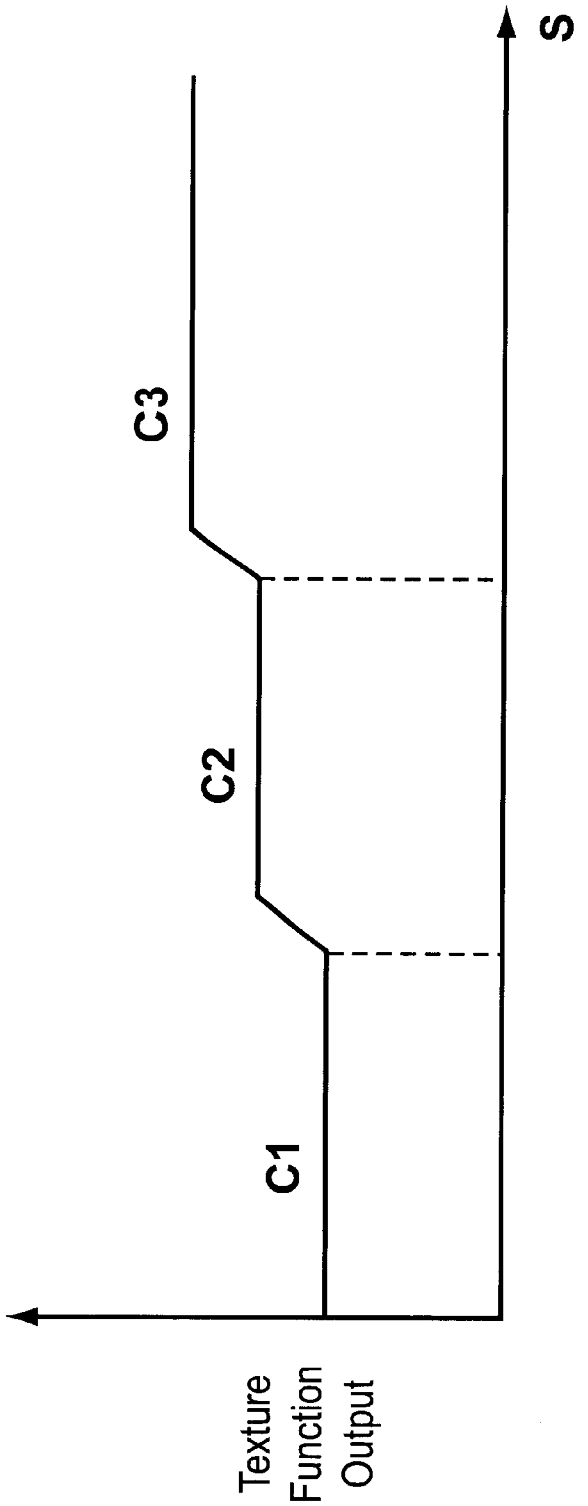


Fig. 8A EXAMPLE TEXTURE FUNCTION
Output = f(S)

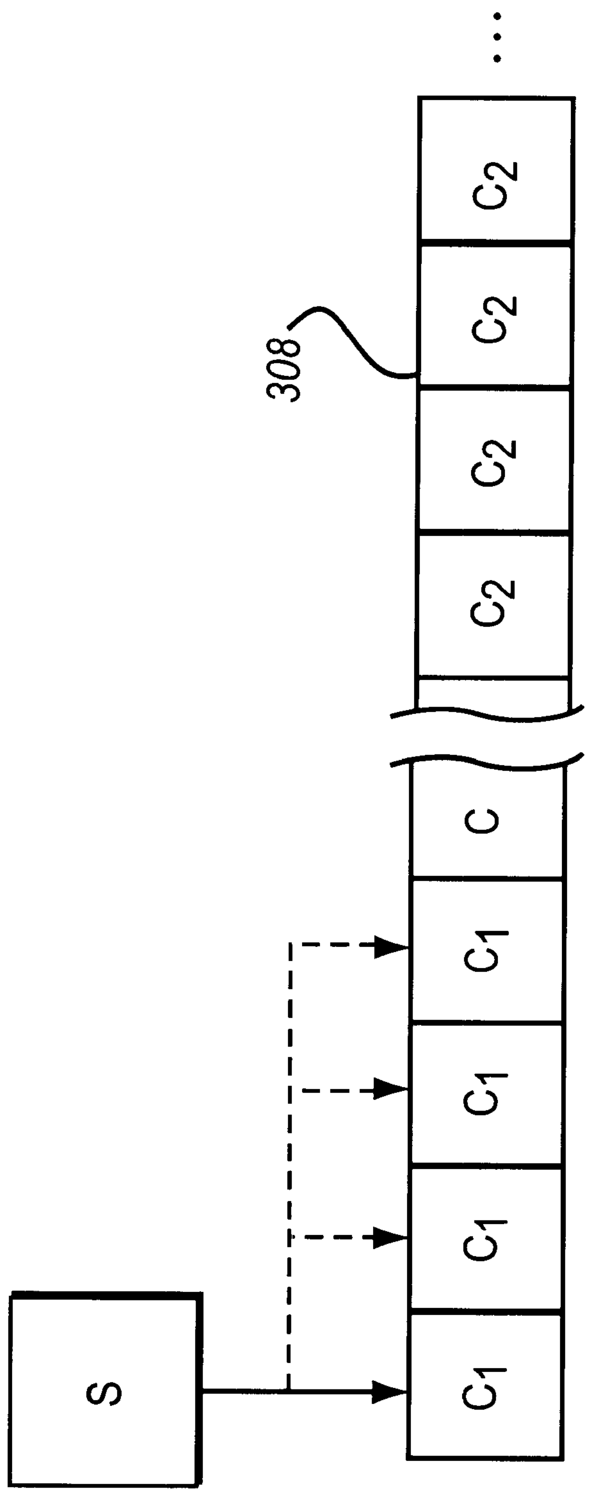


Fig. 8B EXAMPLE 1-D TEXTURE MAPPING

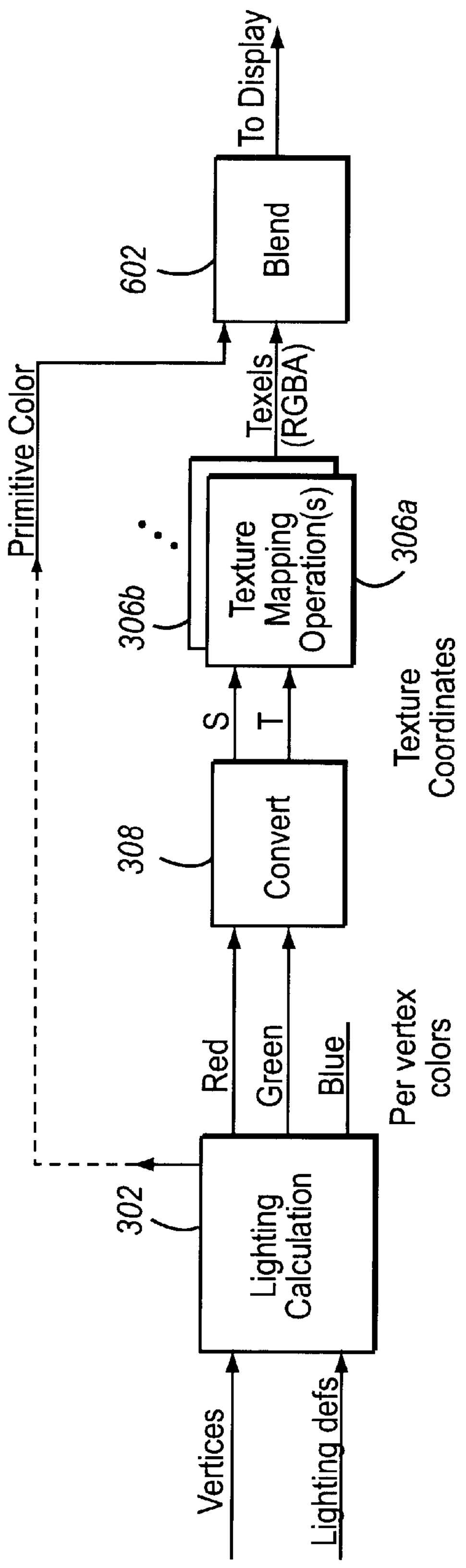
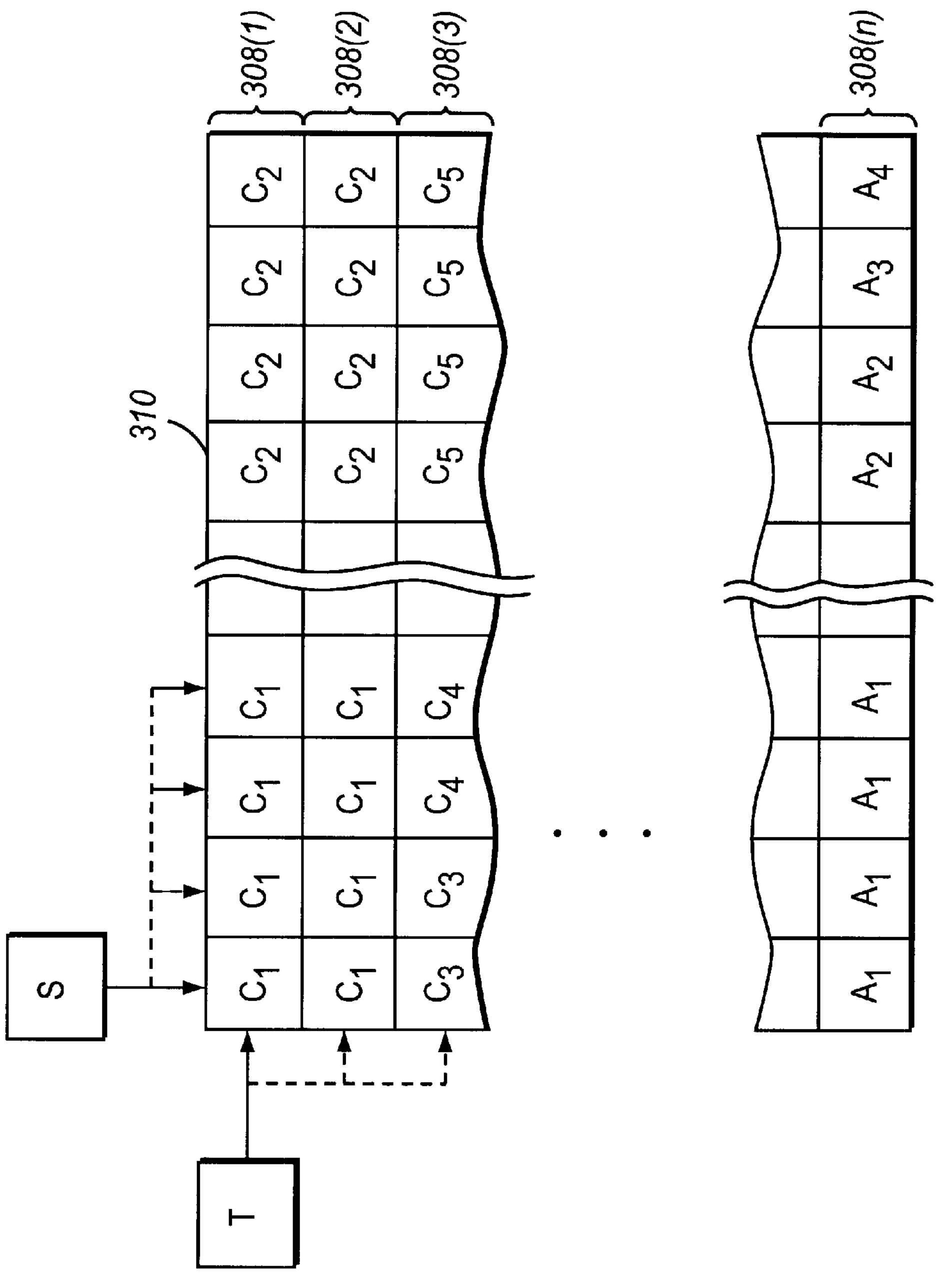


Fig. 9 EXAMPLE TEXTURE MAPPING



S
T
310
308(1)
308(2)
308(3)
308(n)
C_1 C_1 C_1 C_1 C_2 C_2 C_2 C_2
C_1 C_1 C_1 C_1 C_2 C_2 C_2 C_2
C_3 C_3 C_4 C_4 C_5 C_5 C_5 C_5
A_1 A_1 A_1 A_1 A_2 A_2 A_3 A_4

Fig. 10A EXAMPLE 2-D TEXTURE MAPPING

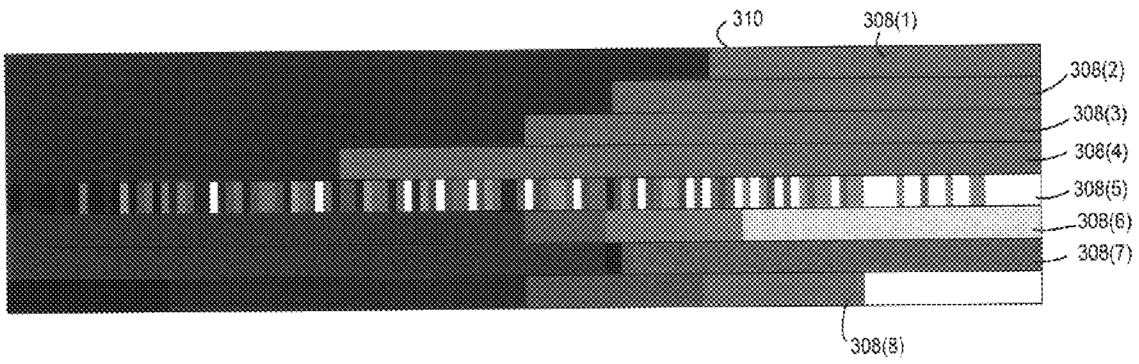


Fig. 10B

EXAMPLE 2D TEXTURE

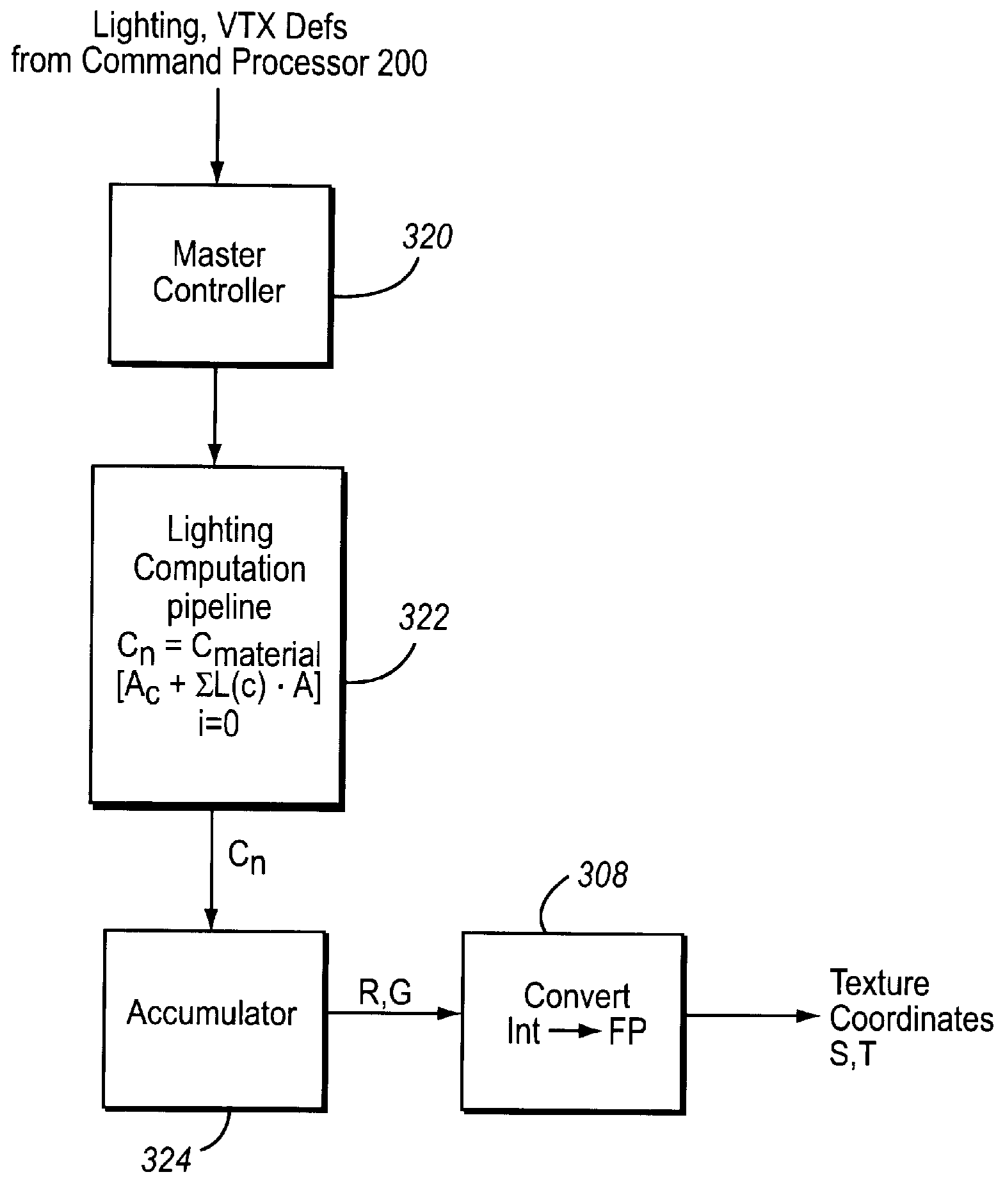

Lighting, VTX Defs from Command Processor 200
Master Controller
320
Lighting Computation pipeline
$C_n = C_{material} [A_c + \Sigma L(c) \cdot A]$
i=0
322
C_n
Accumulator
324
R,G
308
Convert Int → FP
Texture Coordinates S,T

Fig. 11

EXAMPLE LIGHTING PIPELINE IMPLEMENTATION

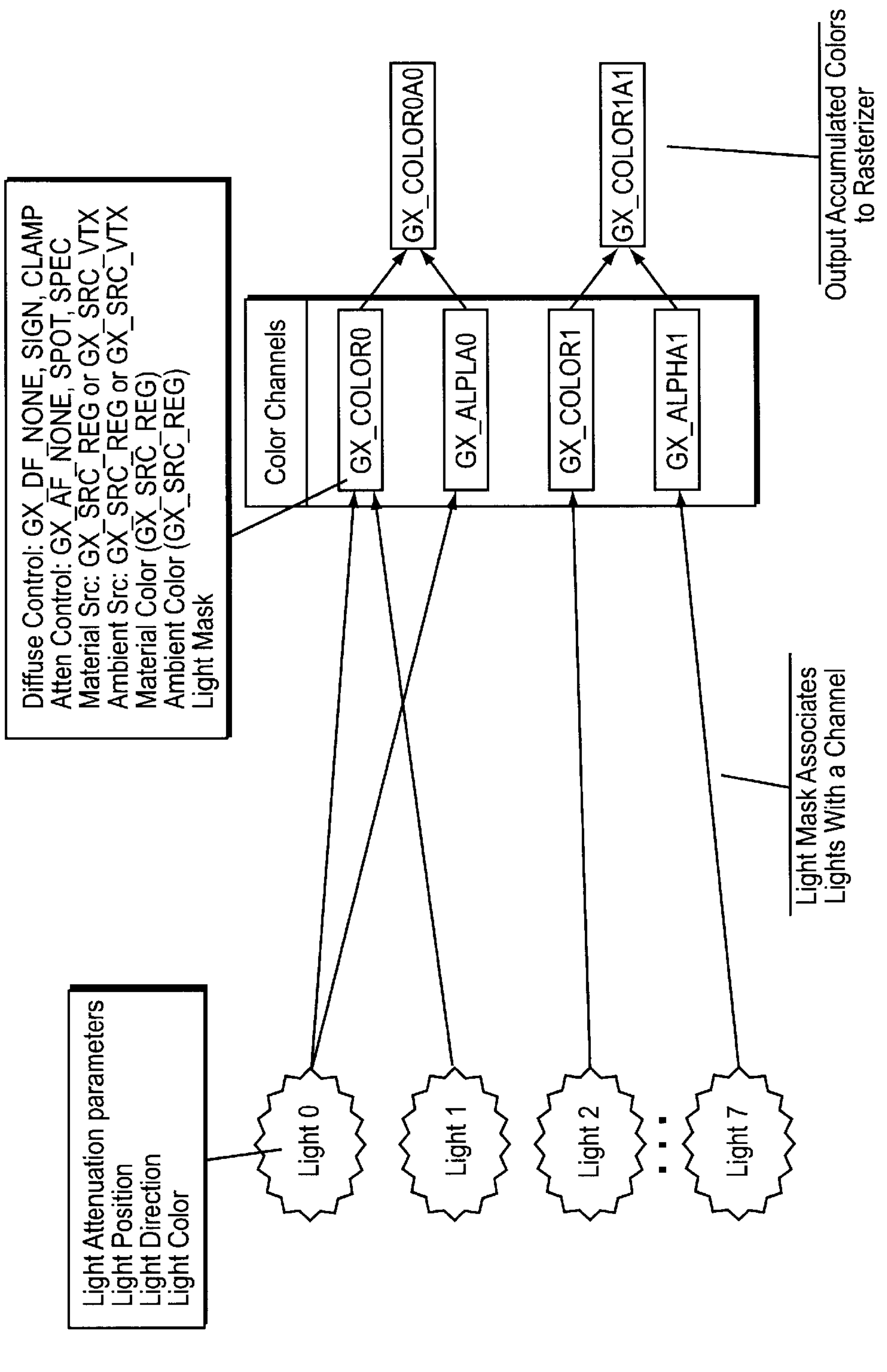

Diffuse Control: GX_DF_NONE, SIGN, CLAMP
Atten Control: GX_AF_NONE, SPOT, SPEC
Material Src: GX_SRC_REG or GX_SRC_VTX
Ambient Src: GX_SRC_REG or GX_SRC_VTX
Material Color (GX_SRC_REG)
Ambient Color (GX_SRC_REG)
Light Mask
GX_COLOR0A0
GX_COLOR1A1
Output Accumulated Colors to Rasterizer
Color Channels
GX_COLOR0
GX_ALPLA0
GX_COLOR1
GX_ALPHA1
Light Mask Associates Lights With a Channel
Light Attenuation parameters
Light Position
Light Direction
Light Color
Light 0
Light 1
Light 2
. . .
Light 7

Fig. 12

ASSOCIATING LIGHTS WITH COLOR CHANNELS

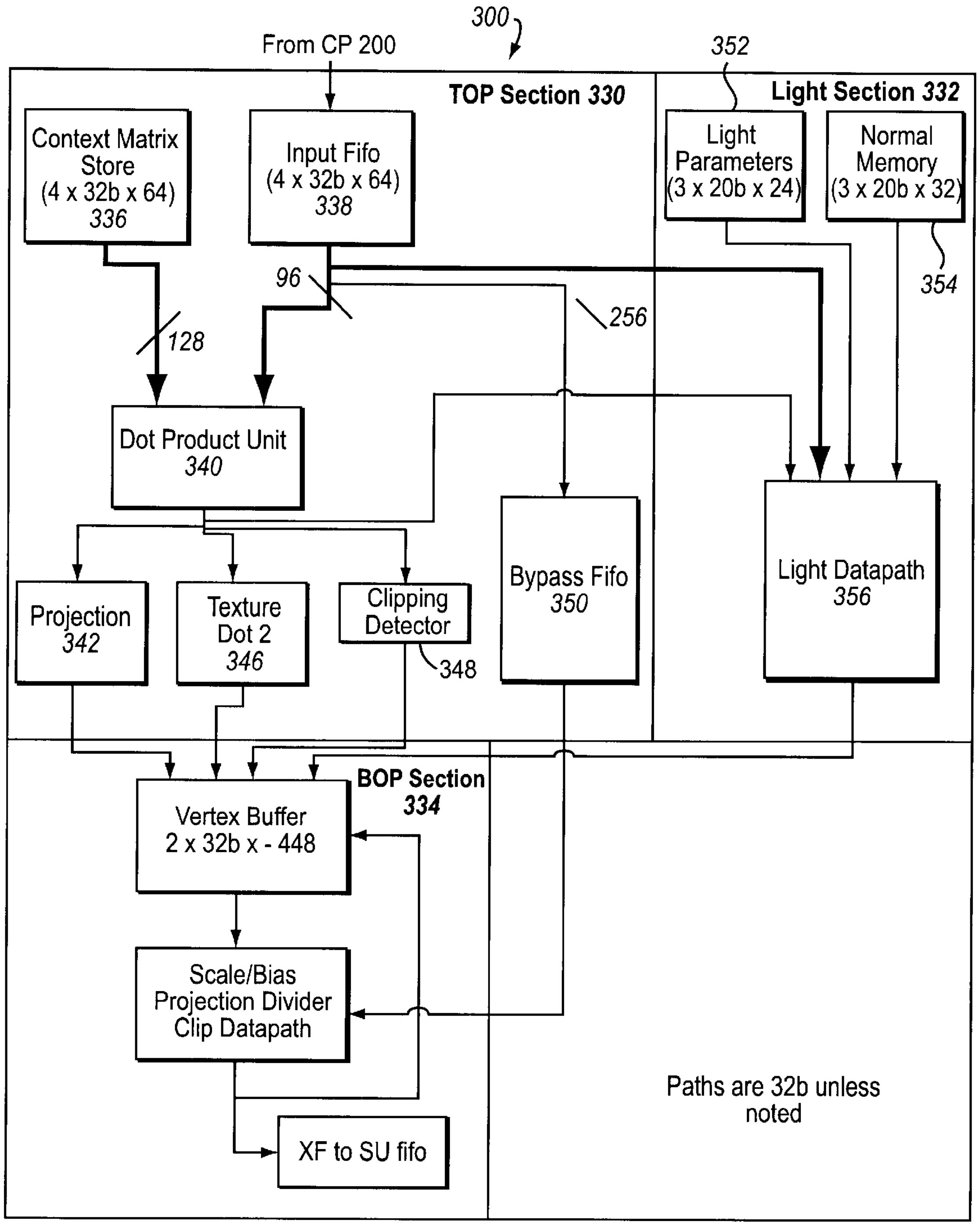

300
From CP 200
TOP Section 330
Light Section 332
352
Context Matrix Store (4 x 32b x 64) 336
Input Fifo (4 x 32b x 64) 338
Light Parameters (3 x 20b x 24)
Normal Memory (3 x 20b x 32)
354
96
128
256
Dot Product Unit 340
Bypass Fifo 350
Light Datapath 356
Projection 342
Texture Dot 2 346
Clipping Detector
348
BOP Section 334
Vertex Buffer 2 x 32b x - 448
Scale/Bias Projection Divider Clip Datapath
XF to SU fifo
Paths are 32b unless noted

Fig. 13
EXAMPLE TRANSFORM UNIT IMPLEMENTATION

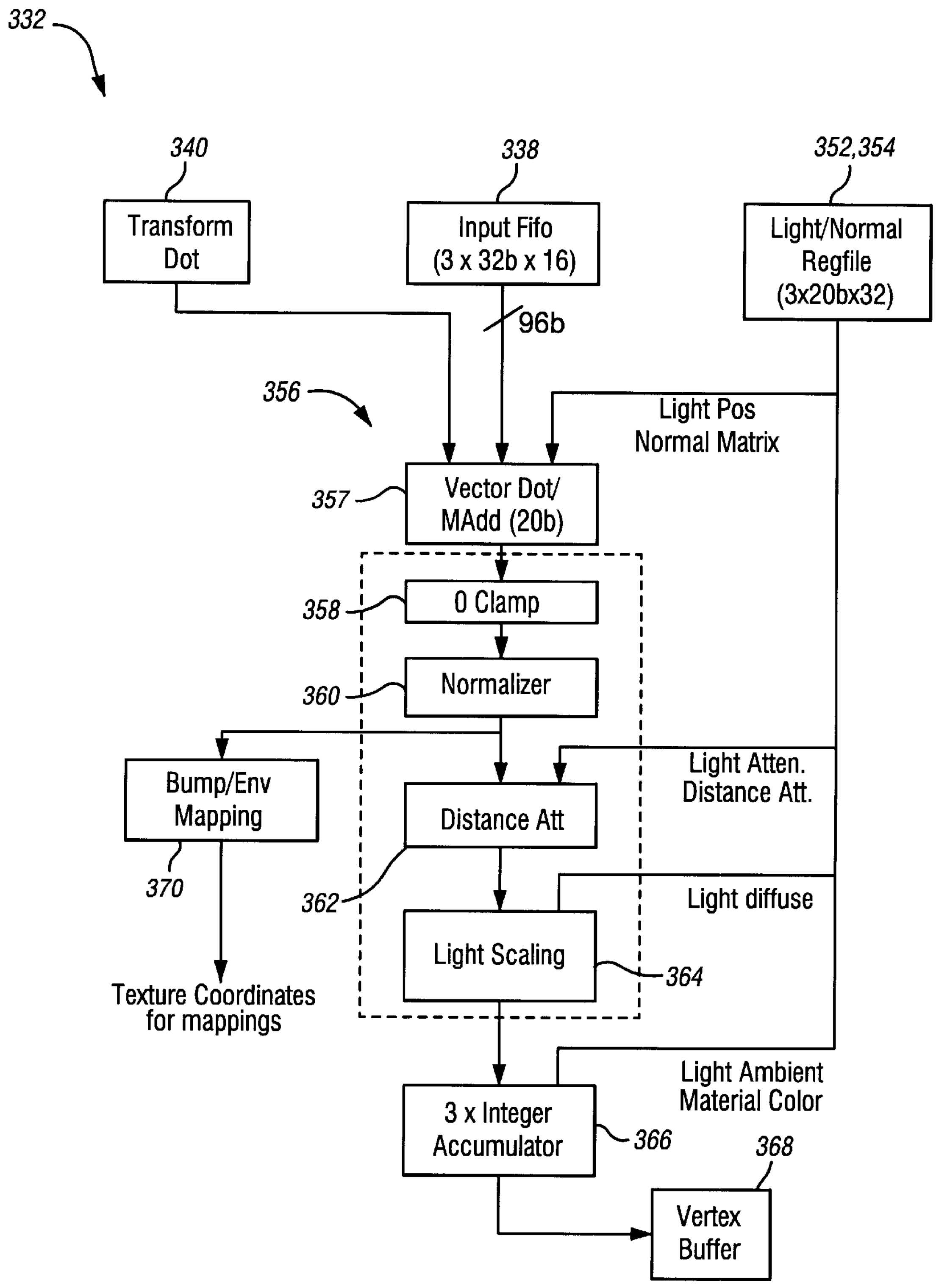


Fig. 14
Example Lighting Pipeline Implementation

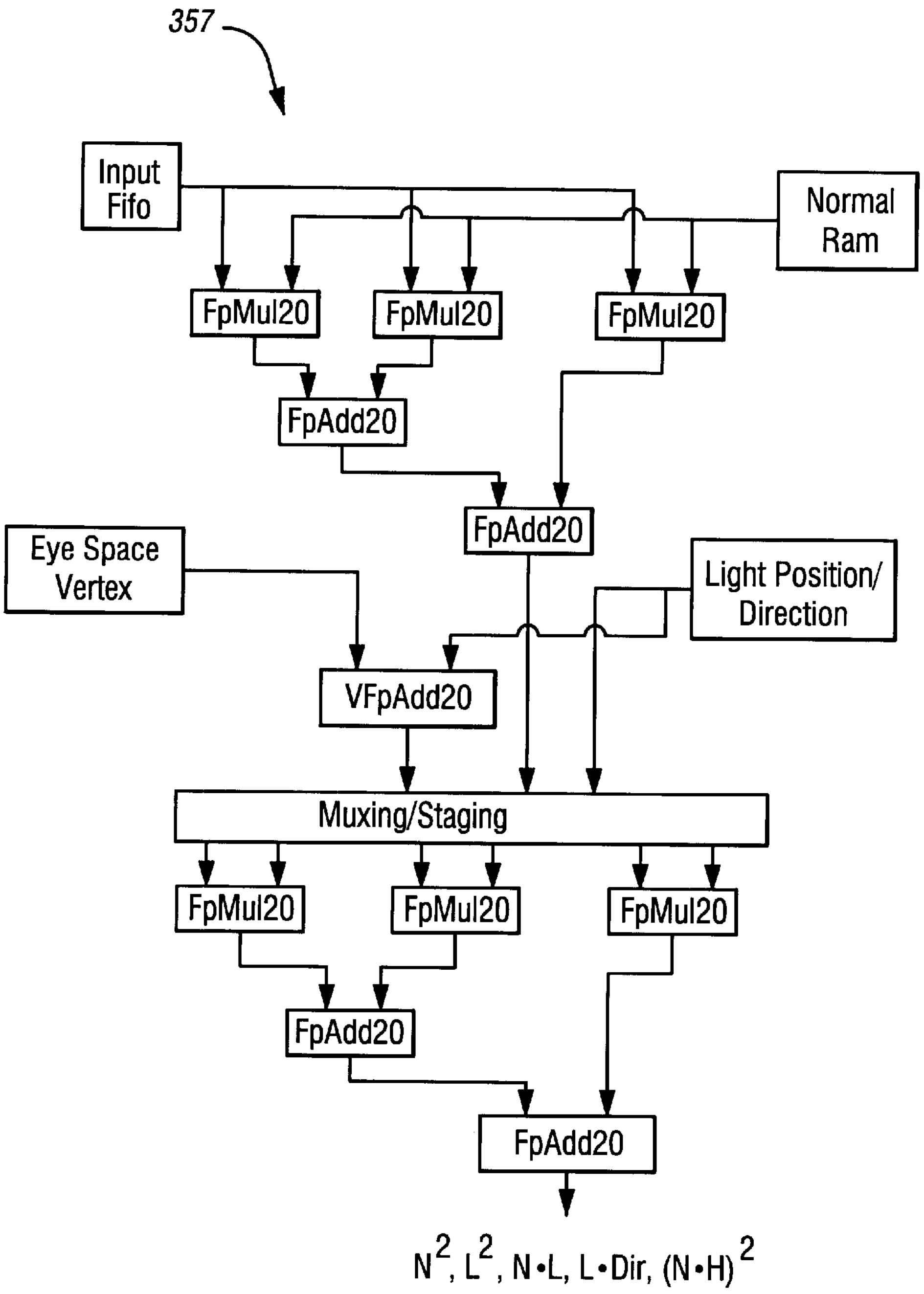


Fig. 15
Example Vector Dot/Add Unit Implementation

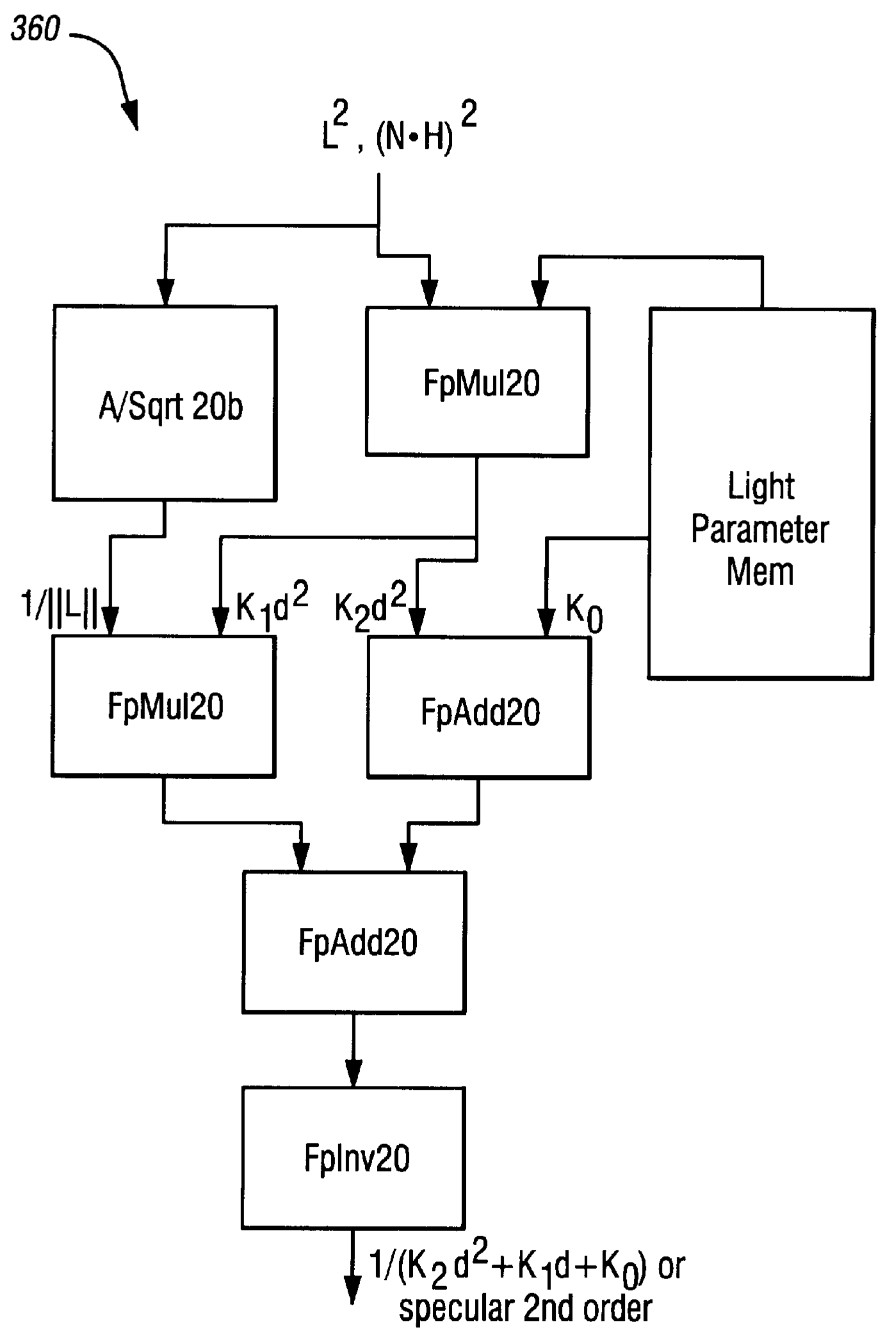


Fig. 16
Example Normalize Implementation

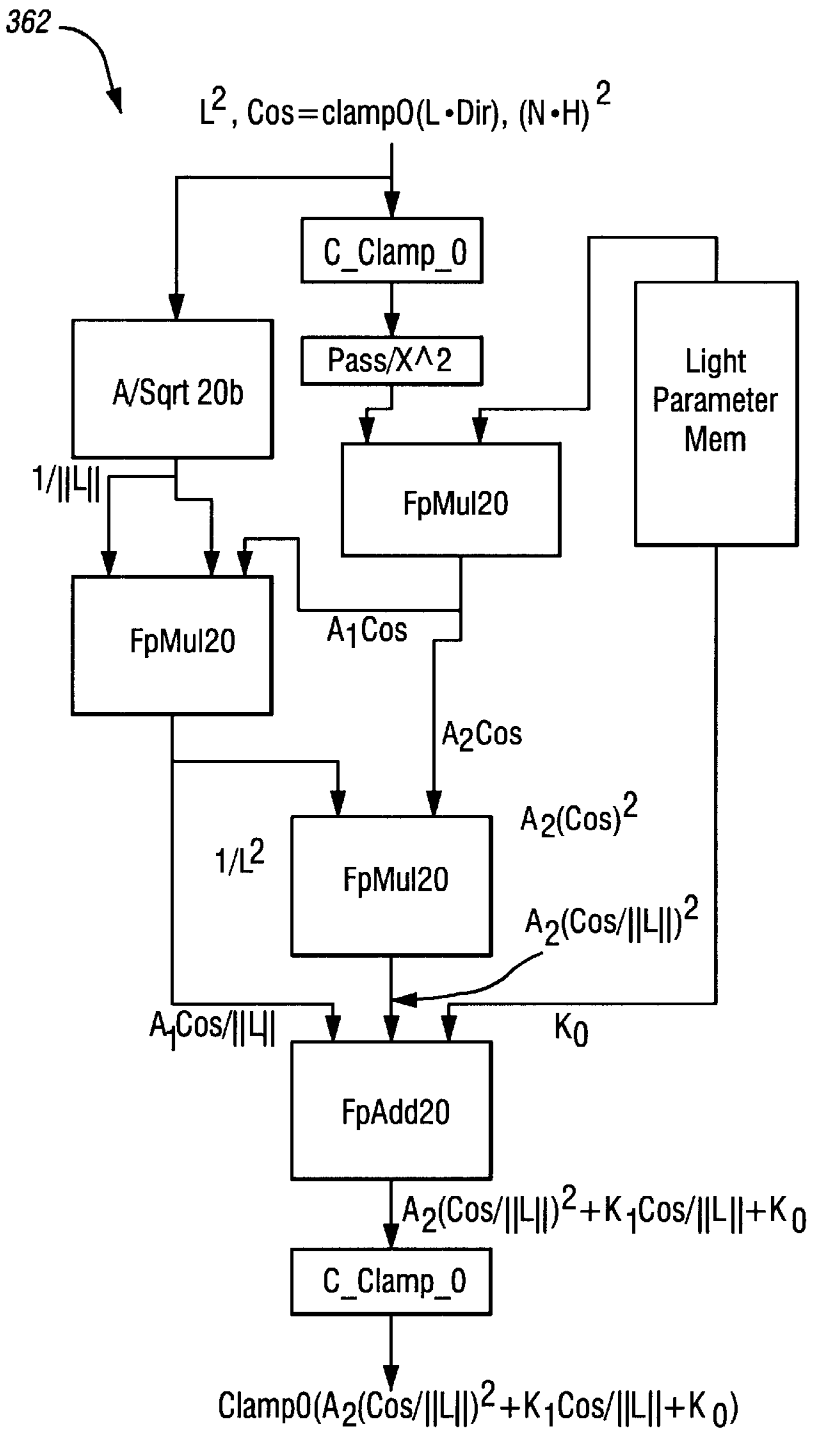


Fig. 17
Example Distance Attenuator Implementation

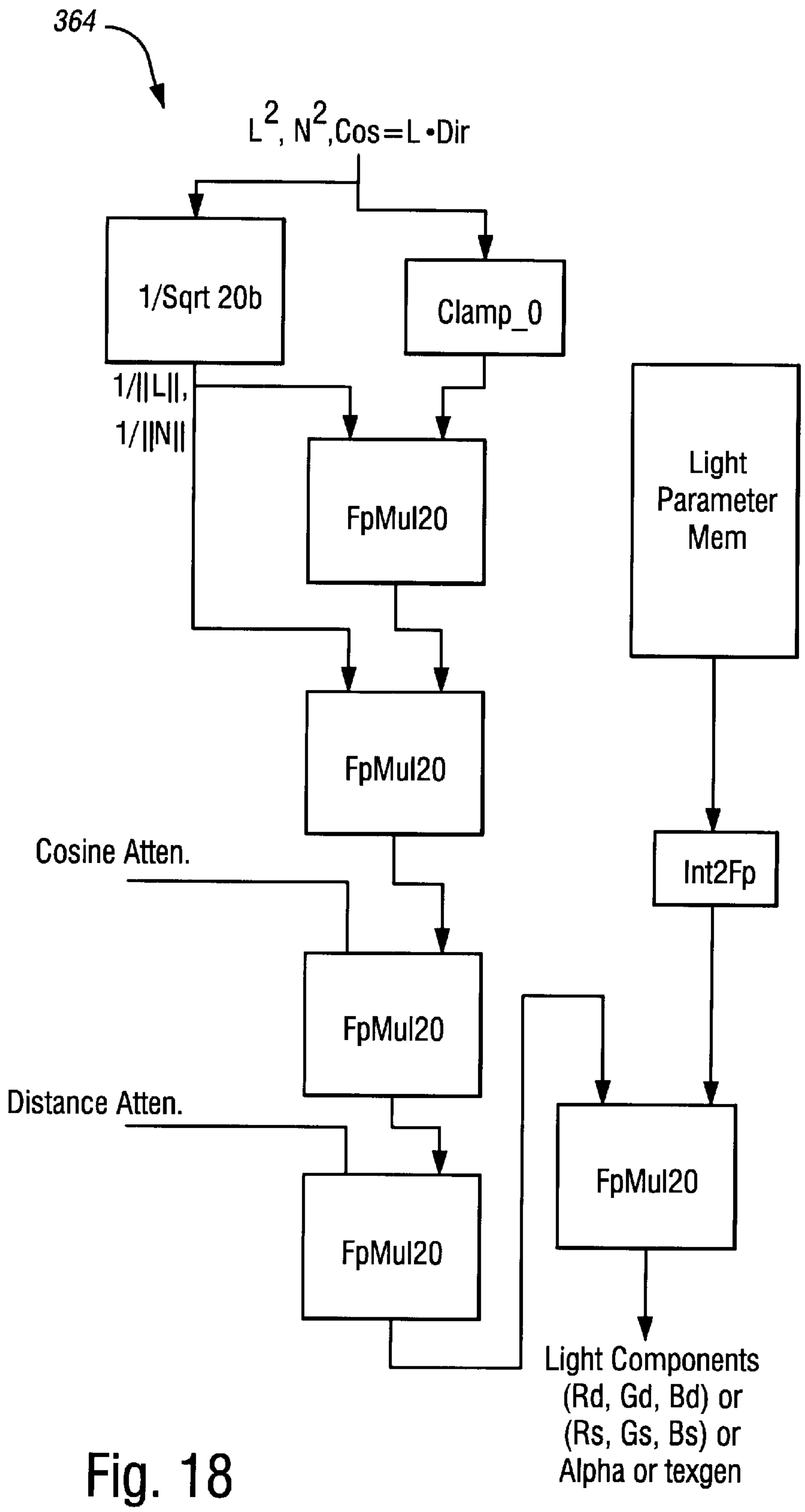
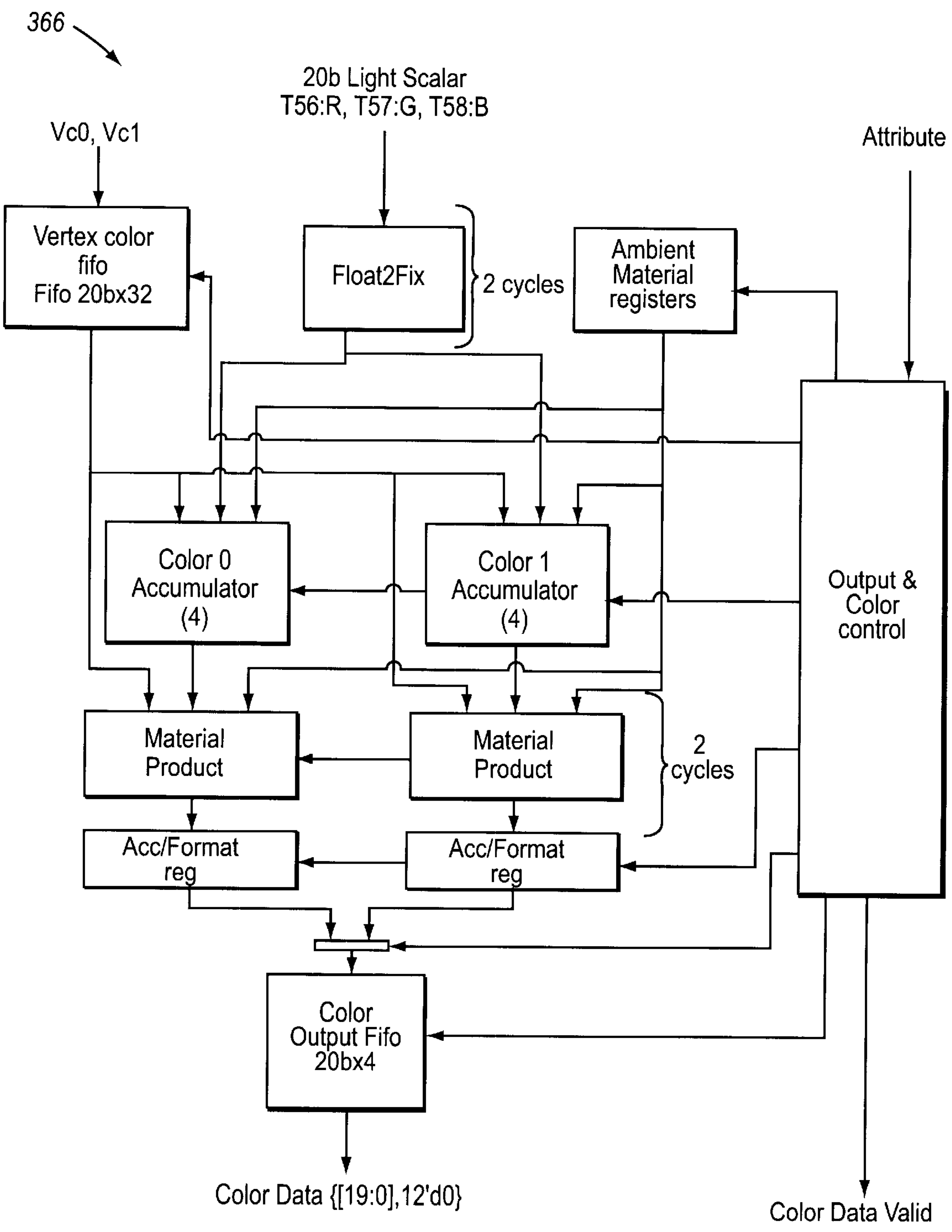


Fig. 18
Example Light Scaler Implementation

Fig. 19 EXAMPLE INTEGER ACCUMULATOR IMPLEMENTATION



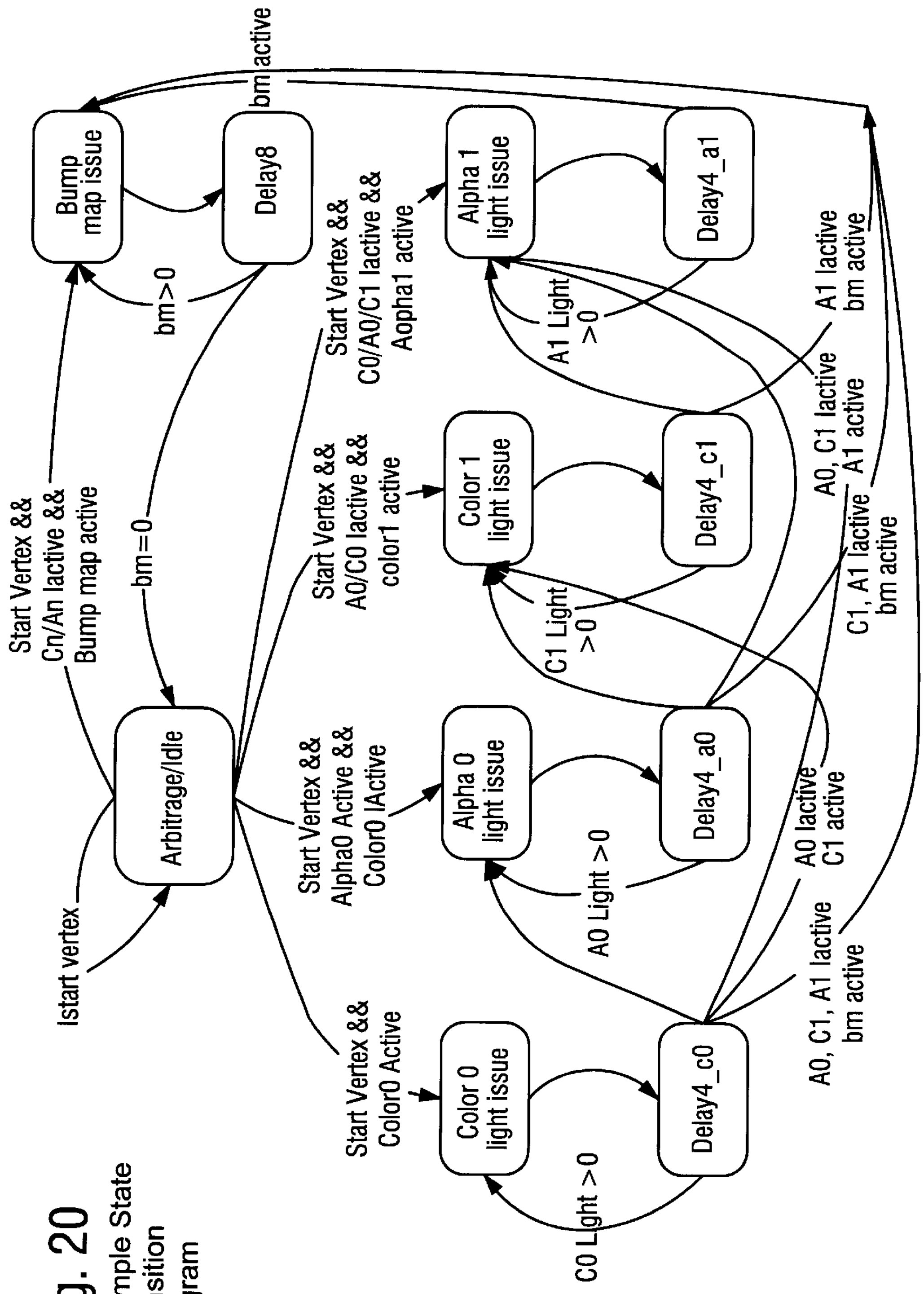


Fig. 20
Example State Transition Diagram

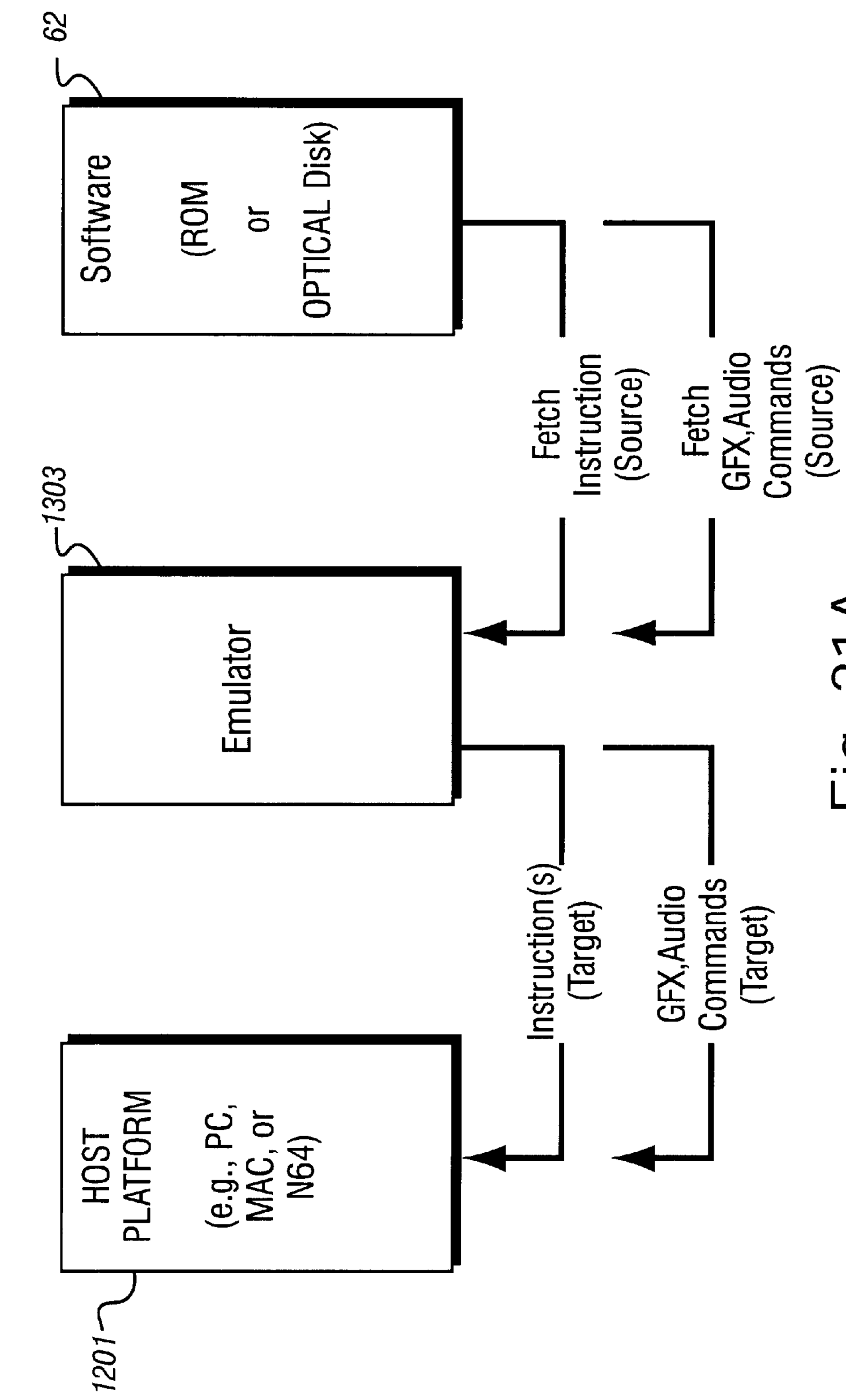
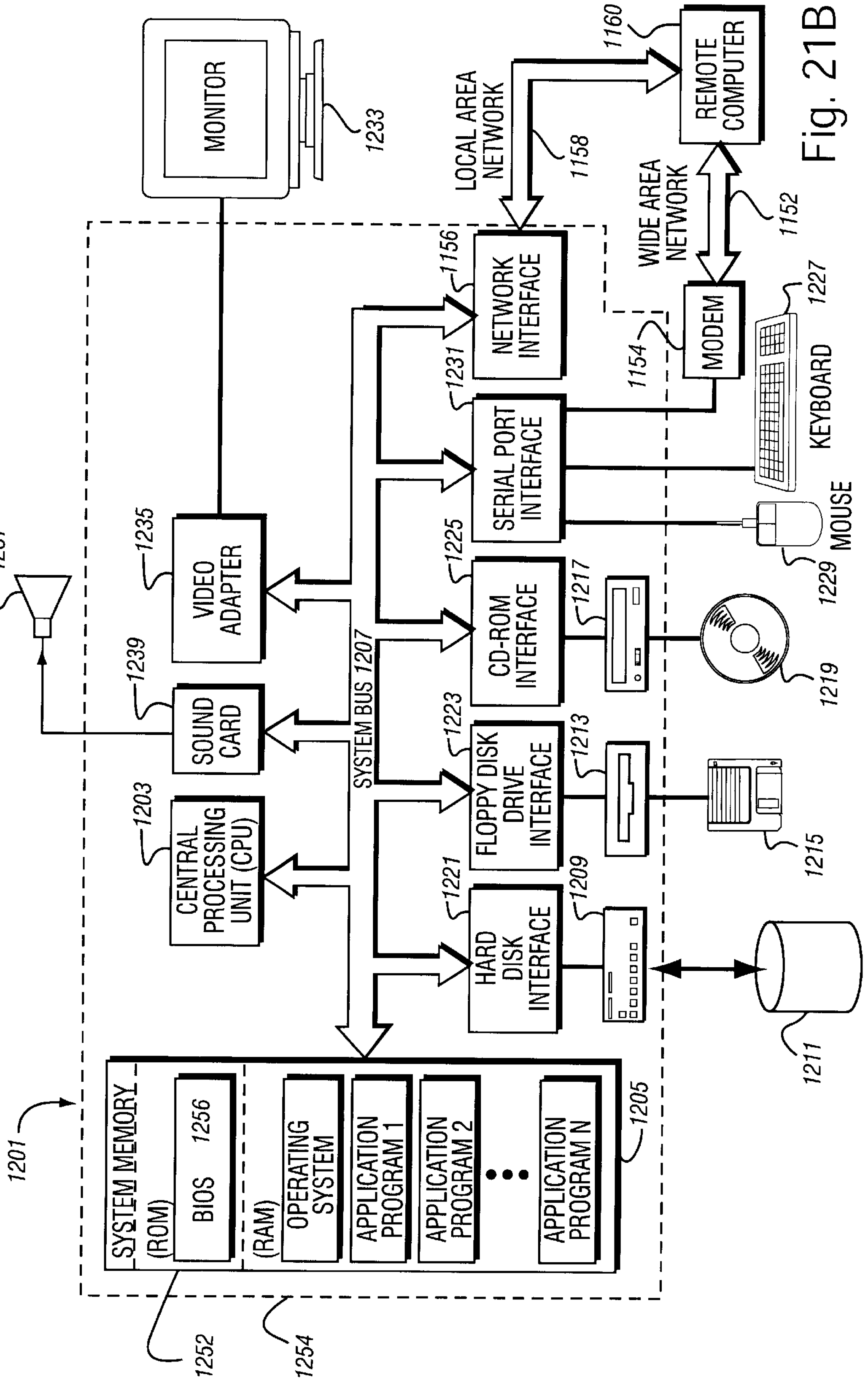

62
Software
(ROM
or
OPTICAL Disk)
1303
Emulator
1201
HOST
PLATFORM
(e.g., PC,
MAC, or
N64)
Fetch
Instruction
(Source)
Fetch
GFX,Audio
Commands
(Source)
Instruction(s)
(Target)
GFX,Audio
Commands
(Target)

Fig. 21A


MONITOR
1233
LOCAL AREA NETWORK
1158
1160
REMOTE COMPUTER
WIDE AREA NETWORK
1152
1237
1235
VIDEO ADAPTER
1156
NETWORK INTERFACE
1154
MODEM
1227
KEYBOARD
1231
SERIAL PORT INTERFACE
MOUSE
1229
1225
CD-ROM INTERFACE
1217
1219
1239
SOUND CARD
SYSTEM BUS 1207
1223
FLOPPY DISK DRIVE INTERFACE
1213
1215
1203
CENTRAL PROCESSING UNIT (CPU)
1221
HARD DISK INTERFACE
1209
1211
1201
SYSTEM MEMORY
(ROM)
BIOS 1256
(RAM)
OPERATING SYSTEM
APPLICATION PROGRAM 1
APPLICATION PROGRAM 2
APPLICATION PROGRAM N
1205
1252
1254
Fig. 21B

ACHROMATIC LIGHTING IN A GRAPHICS SYSTEM AND METHOD

This application claims the benefit of U.S. Provisional Application No. 60/227,007, filed Aug. 23, 2000, the entire content of which is hereby incorporated by reference in this application.

FIELD OF THE INVENTION

The present invention relates to computer graphics, and more particularly to interactive graphics systems such as home video game platforms. More particularly, this invention relates to a graphics processing improvement that uses a lighting function to produce a parameter for subsequent use in changing a color or opacity. Still more particularly, the invention relates to a **3**D graphics system wherein a lighting calculation defines a parameter such as distance or angle that is applied to a further function (e.g., texturing).

BACKGROUND AND SUMMARY OF THE INVENTION

Many of us have seen films containing remarkably realistic dinosaurs, aliens, animated toys and other fanciful creatures. Such animations are made possible by computer graphics. Using such techniques, a computer graphics artist can specify how each object should look and how it should change in appearance over time, and a computer then models the objects and displays them on a display such as your television or a computer screen. The computer takes care of performing the many tasks required to make sure that each part of the displayed image is colored and shaped just right based on the position and orientation of each object in a scene, the direction in which light seems to strike each object, the surface texture of each object, and other factors.

Because computer graphics generation is complex, computer-generated three-dimensional graphics just a few years ago were mostly limited to expensive specialized flight simulators, high-end graphics workstations and supercomputers. The public saw some of the images generated by these computer systems in movies and expensive television advertisements, but most of us couldn't actually interact with the computers doing the graphics generation. All this has changed with the availability of relatively inexpensive 3D graphics platforms such as, for example, the Nintendo 64® and various 3D graphics cards now available for personal computers. It is now possible to interact with exciting 3D animations and simulations on relatively inexpensive computer graphics systems in your home or office.

It has long been known to perform lighting calculations in a 3-D graphics systems based on a variety of parameters (e.g., distance attenuation, angle, beam lighting, etc.). Traditionally, the results of such lighting calculations were used to modify the color and/or opacity of the object being displayed—as is documented in a variety of standard reference materials on computer graphics (see for example, Foley et al, *Computer Graphics Principles and Practice* (2d. Ed. 1990) at Chapter 16 ("Illumination and Shading"); and Moller et al, *Real Time Rendering* (A K Peters 1999) at Section 4.3 et seq. ("Lighting and Shading"); Rogers et al, *Procedural Elements for Computer Graphics* (2d Ed. McGraw-Hill 1997) at Section 5.2 et. seq. ("Illumination Models"); Neider et al, *OpenGL Programming Guide* (Addison-Wesley 1993) at Chapter 6 ("Lighting"); and Kovach, *Inside Direct3D* (Microsoft Press 2000) at Chapter 5 ("Direct3D Vertices and the Transformation and Lighting Pipeline"). For example, techniques known as Gouraud

shading and Phong shading modify the color of a displayed surface depending on a lighting effect modeled by a lighting equation. As one example, shining a bright spotlight on a shiny surface can have the effect of whitening the surface color at points where the light is shining. This is often accomplished in a conventional graphics system by having the rasterizer determine the color of each pixel of the displayed surface of a primitive based on the primitive's color (often defined on a vertex-by-vertex basis) and on the result of the lighting equation(s).

A problem graphics system designers confronted in the past was how to efficiently create non-photorealistic images such as cartoon characters. For many years, most of the work in the graphics field was devoted to creating images that are as realistic as photographs. More recently, however, there has been an interest in non-photorealistic imaging.

One type of non-photorealistic imaging that has recently generated interest is the process of automating the imaging of cartoon characters. During the heyday of hand drawn cartooning in the 1930s and 1940s, artists created wonderful cartoon characters that dynamically changed from frame to frame. These hand drawn cartoons in many ways set the standard for cartoon rendering. The cartoons were not intended to appear realistic. To the contrary, the cartoons were designed to appear as caricatures. For example, in such cartoons, a person's face might appear to be pasty white with rosy red cheeks defined by brilliantly red or reddish-pink coloration. As the character moved through the scene, the cheek coloration might change dynamically as the artist hand-colored each frame. Such dynamic effects are fascinating to watch and add interest to the cartoon images.

Unfortunately, the hand-drawn cartoon artistry of the 1930s and 1940s was very time consuming and expensive. Moreover, people now want to use video and computer games to interact with cartoon characters. While video games have for a number of years been successful in dynamically rendering cartoon characters interactively, they have never achieved the hand-drawn artistry details of latter-day hand-drawn cartoons. While much work has been done on high end type systems for authoring cartoon and other non-photorealistic images, further improvements are possible and desirable.

The present invention provides improvements in non-photorealistic and other imaging effects that can be implemented using a low cost graphics system such as, for example, a home video game platform or a personal computer graphics accelerator.

In accordance with one aspect provided by this invention, the lighting function of the type typically used to light objects within a scene is used to produce a parameter other than color. Such a parameter is used to modify a color or opacity of an object.

In accordance with another aspect provided by this invention, a lighting calculation performs per-vertex lighting to provide conventional color component outputs. The color component outputs are applied to a texturing function that processes the color components as achromatic parameters. The texturing function output provides a visualization effect (e.g., color and/or opacity modified based on the achromatic parameters) that is used to contribute to the visualization of a rendered scene.

In accordance with yet another aspect provided by this invention, the lighting calculation output provides three color components one of which is discarded. The other two color components are converted into texture coordinates and used in a texture mapping operation. One of the texture coordinates selects a one-dimensional texture map within a two-dimensional table. The other texture coordinate selects a particular texel within the selected one-dimensional texture map. The resulting selected texel provides color and/or alpha information that is applied to a surface defined by the vertex.

In accordance with yet another aspect provided by this invention, non-photorealistic cartoon lighting effects are provided in a real time 3D graphics system by using a lighting calculation to produce a parameter other than color or opacity. A one-dimensional texture map can be defined specifying different brush strokes as a function of the parameter. A conventional texture mapping operation can be used to map the one-dimensional texture map onto a polygon surface based on the parameter.

In more detail, the disclosed system can provide conventional lighting-based shading (as discussed above) as part of its overall operation, but provides an additional enhancement that allows the lighting equation(s) to generate a texture coordinate (i.e., a parameter other than color or opacity). That other parameter may be inputted to a further function (e.g., a lookup table stored as a texture) to provide a further result—which may in turn change the color/opacity of an object. This intermediate step of, having the lighting calculation produce a parameter that only indirectly affects color and/or opacity of a displayed object provides additional flexibility beyond conventional approaches that use the lighting equation output to directly affect primitive surface color.

A particular example embodiment uses the lighting equation result to select a one-dimensional texture from a number of textures. As an example, to display a tree trunk you might define two different one-dimensional textures—one having a range of silvers and the other having a range of browns. The lighting equation could be used to determine the angle at which a light source is striking the tree trunk, with the result selecting between the two textures. The tree trunk could be colored (using conventional texture mapping) with a range of different silvers from an oblique angle but with a range of browns/blacks when the light is striking it head-on. In such a case, the lighting equation selects a one-dimensional texture (i.e., it is acting as a parameter other than color or opacity—in this particular example, selecting between two different textures).

In the particular embodiment disclosed herein, improvements are made to the transformation and lighting ("T & L") pipeline to allow it to generate a texture coordinate(s) based on the lighting equation. The transformation and lighting develops the lighting equation output, but instead of providing it directly to change the pixel color/opacity generated by the rasterizer, it provides the result as a texture coordinate to a texture unit. In the disclosed embodiment, the output of the texture unit is a color or opacity that is blended with the object's primitive color/opacity (e.g., as developed by transform and lighting pipeline and the rasterizer in a conventional fashion based on the same or different lighting equation using a conventional shading algorithm such as Gouraud or Phong shading) to provide a modified color/opacity value for display.

BRIEF DESCRIPTION OF THE DRAWINGS

These and other features and advantages provided by the invention will be better and more completely understood by referring to the following detailed description of presently preferred embodiments in conjunction with the drawings. The file of this patent contains at least one drawing executed in color. Copies of this patent with color drawing(s) will be provided by the Patent and Trademark Office upon request and payment of the necessary fee. The drawings are briefly described as follows:

FIG. **1** is an overall view of an example interactive computer graphics system;

FIG. **2** is a block diagram of the FIG. **1** example computer graphics system;

FIG. **3** is a block diagram of the example graphics and audio processor shown in FIG. **2**;

FIG. **4** is a block diagram of the example 3D graphics processor shown in FIG. **3**;

FIG. **5** is an example logical flow diagram of the FIG. **4** graphics and audio processor;

FIG. **6** shows an example high-level image generating process provided by this invention;

FIG. **7** shows a more specific image generating process provided by this invention that uses texturing based on an achromatic lighting parameter;

FIG. **8**A shows an example texture function;

FIG. **8**B shows an example one-dimensional texture map;

FIG. **9** shows an example texture mapping procedure;

FIG. **10**A shows an example two-dimensional texture map;

FIG. **10**B shows a further example two-dimensional texture map;

FIG. **11** shows an example lighting pipeline implementation;

FIG. **12** shows an example association of lights with color channels;

FIG. **13** shows an example transform unit implementation;

FIG. **14** shows an example lighting pipeline implementation;

FIG. **15** shows an example vector dot/add unit implementation;

FIG. **16** shows an example normalizer implementation;

FIG. **17** shows an example distance attenuator implementation;

FIG. **18** shows an example light scaler implementation;

FIG. **19** shows an example integer accumulator implementation;

FIG. **20** shows an example state transition diagram; and

FIGS. **21**A and **21**B show example alternative compatible implementations.

DETAILED DESCRIPTION OF EXAMPLE EMBODIMENTS OF THE INVENTION

FIG. **1** shows an example interactive 3D computer graphics system **50**. System **50** can be used to play interactive 3D video games with interesting stereo sound. It can also be used for a variety of other applications.

In this example, system **50** is capable of processing, interactively in real time, a digital representation or model of a three-dimensional world. System **50** can display some or all of the world from any arbitrary viewpoint. For example, system **50** can interactively change the viewpoint in response to real time inputs from handheld controllers **52***a*, **52***b* or other input devices. This allows the game player to see the world through the eyes of someone within or outside of the world. System **50** can be used for applications that do not require real time 3D interactive display (e.g., 2D display generation and/or non-interactive display), but the capability of displaying quality 3D images very quickly can be used to create very realistic and exciting game play or other graphical interactions.

To play a video game or other application using system **50**, the user first connects a main unit **54** to his or her color television set **56** or other display device by connecting a cable **58** between the two. Main unit **54** produces both video signals and audio signals for controlling color television set **56**. The video signals are what controls the images displayed on the television screen **59**, and the audio signals are played back as sound through television stereo loudspeakers **61**L, **61**R.

The user also needs to connect main unit **54** to a power source. This power source may be a conventional AC adapter (not shown) that plugs into a standard home electrical wall socket and converts the house current into a lower DC voltage signal suitable for powering the main unit **54**. Batteries could be used in other implementations.

The user may use hand controllers **52***a*, **52***b* to control main unit **54**. Controls **60** can be used, for example, to specify the direction (up or down, left or right, closer or further away) that a character displayed on television **56** should move within a 3D world. Controls **60** also provide input for other applications (e.g., menu selection, pointer/cursor control, etc.). Controllers **52** can take a variety of forms. In this example, controllers **52** shown each include controls **60** such as joysticks, push buttons and/or directional switches. Controllers **52** may be connected to main unit **54** by cables or wirelessly via electromagnetic (e.g., radio or infrared) waves.

To play an application such as a game, the user selects an appropriate storage medium **62** storing the video game or other application he or she wants to play, and inserts that storage medium into a slot **64** in main unit **54**. Storage medium **62** may, for example, be a specially encoded and/or encrypted optical and/or magnetic disk. The user may operate a power switch **66** to turn on main unit **54** and cause the main unit to begin running the video game or other application based on the software stored in the storage medium **62**. The user may operate controllers **52** to provide inputs to main unit **54**. For example, operating a control **60** may cause the game or other application to start. Moving other controls **60** can cause animated characters to move in different directions or change the user's point of view in a 3D world. Depending upon the particular software stored within the storage medium **62**, the various controls **60** on the controller **52** can perform different functions at different times.

EXAMPLE ELECTRONICS OF OVERALL SYSTEM

FIG. **2** shows a block diagram of example components of system **50**. The primary components include:

- a main processor (CPU) **110**,
- a main memory **112**, and
- a graphics and audio processor **114**.

In this example, main processor **110** (e.g., an enhanced IBM Power PC 750) receives inputs from handheld controllers **108** (and/or other input devices) via graphics and audio processor **114**. Main processor **110** interactively responds to user inputs, and executes a video game or other program supplied, for example, by external storage media **62** via a mass storage access device **106** such as an optical disk drive. As one example, in the context of video game play, main processor **110** can perform collision detection and animation processing in addition to a variety of interactive and control functions.

In this example, main processor **110** generates 3D graphics and audio commands and sends them to graphics and audio processor **114**. The graphics and audio processor **114** processes these commands to generate interesting visual images on display **59** and interesting stereo sound on stereo loudspeakers **61**R, **61**L or other suitable sound-generating devices.

Example system **50** includes a video encoder **120** that receives image signals from graphics and audio processor **114** and converts the image signals into analog and/or digital video signals suitable for display on a standard display device such as a computer monitor or home color television set **56**. System **50** also includes an audio codec (compressor/decompressor) **122** that compresses and decompresses digitized audio signals and may also convert between digital and analog audio signaling formats as needed. Audio codec **122** can receive audio inputs via a buffer **124** and provide them to graphics and audio processor **114** for processing (e.g., mixing with other audio signals the processor generates and/or receives via a streaming audio output of mass storage access device **106**). Graphics and audio processor **114** in this example can store audio related information in an audio memory **126** that is available for audio tasks. Graphics and audio processor **114** provides the resulting audio output signals to audio codec **122** for decompression and conversion to analog signals (e.g., via buffer amplifiers **128**L, **128**R) so they can be reproduced by loudspeakers **61**L, **61**R.

Graphics and audio processor **114** has the ability to communicate with various additional devices that may be present within system **50**. For example, a parallel digital bus **130** may be used to communicate with mass storage access device **106** and/or other components. A serial peripheral bus **132** may communicate with a variety of peripheral or other devices including, for example:

- a programmable read-only memory and/or real time clock **134**,
- a modem **136** or other networking interface (which may in turn connect system **50** to a telecommunications network **138** such as the Internet or other digital network from/to which program instructions and/or data can be downloaded or uploaded), and
- flash memory **140**.

A further external serial bus **142** may be used to communicate with additional expansion memory **144** (e.g., a memory card) or other devices. Connectors may be used to connect various devices to busses **130**, **132**, **142**.

EXAMPLE GRAPHICS AND AUDIO PROCESSOR

FIG. **3** is a block diagram of an example graphics and audio processor **114**. Graphics and audio processor **114** in one example may be a single-chip ASIC (application specific integrated circuit). In this example, graphics and audio processor **114** includes:

- a processor interface **150**,
- a memory interface/controller **152**,
- a 3D graphics processor **154**,
- an audio digital signal processor (DSP) **156**,
- an audio memory interface **158**,
- an audio interface and mixer **160**,
- a peripheral controller **162**, and
- a display controller **164**.

3D graphics processor **154** performs graphics processing tasks. Audio digital signal processor **156** performs audio processing tasks. Display controller **164** accesses image information from main memory **112** and provides it to video encoder **120** for display on display device **56**. Audio interface and mixer **160** interfaces with audio codec **122**, and can also mix audio from different sources (e.g., streaming audio from mass storage access device **106**, the output of audio DSP **156**, and external audio input received via audio codec **122**). Processor interface **150** provides a data and control interface between main processor **110** and graphics and audio processor **114**.

Memory interface **152** provides a data and control interface between graphics and audio processor **114** and-memory **112**. In this example, main processor **110** accesses main memory **112** via processor interface **150** and memory interface **152** that are part of graphics and audio processor **114**. Peripheral controller **162** provides a data and control interface between graphics and audio processor **114** and the various peripherals mentioned above. Audio memory interface **158** provides an interface with audio memory **126**.

EXAMPLE GRAPHICS PIPELINE

FIG. **4** shows a more detailed view of an example 3D graphics processor **154**. 3D graphics processor **154** includes, among other things, a command processor **200** and a 3D graphics pipeline **180**. Main processor **110** communicates streams of data (e.g., graphics command streams and display lists) to command processor **200**. Main processor **110** has a two-level cache **115** to minimize memory latency, and also has a write-gathering buffer **111** for uncached data streams targeted for the graphics and audio processor **114**. The write-gathering buffer **111** collects partial cache lines into full cache lines and sends the data out to the graphics and audio processor **114** one cache line at a time for maximum bus usage.

Command processor **200** receives display commands from main processor **110** and parses them—obtaining any additional data necessary to process them from shared memory **112**. The command processor **200** provides a stream of vertex commands to graphics pipeline **180** for 2D and/or 3D processing and rendering. Graphics pipeline **180** generates images based on these commands. The resulting image information may be transferred to main memory **112** for access by display controller/video interface unit **164**—which displays the frame buffer output of pipeline **180** on display **56**.

FIG. **5** is a logical flow diagram of graphics processor **154**. Main processor **110** may store graphics command streams **210**, display lists **212** and vertex arrays **214** in main memory **112**, and pass pointers to command processor **200** via bus interface **150**. The main processor **110** stores graphics commands in one or more graphics first-in-first-out (FIFO) buffers **210** it allocates in main memory **110**. The command processor **200** fetches:

- command streams from main memory **112** via an on-chip FIFO memory buffer **216** that receives and buffers the graphics commands for synchronization/flow control and load balancing,
- display lists **212** from main memory **112** via an on-chip call FIFO memory buffer **218**, and
- vertex attributes from the command stream and/or from vertex arrays **214** in main memory **112** via a vertex cache **220**.

Command processor **200** performs command processing operations **200***a* that convert attribute types to floating point format, and pass the resulting complete vertex polygon data to graphics pipeline **180** for rendering/rasterization. A programmable memory arbitration circuitry **130** (see FIG. **4**) arbitrates access to shared main memory **112** between graphics pipeline **180**, command processor **200** and display controller/video interface unit **164**.

FIG. **4** shows that graphics pipeline **180** may include:

- a transform unit **300**,
- a setup/rasterizer **400**,
- a texture unit **500**,
- a texture environment unit **600**, and a pixel engine **700**.

Transform unit **300** performs a variety of 2D and 3D transform and other operations **300***a* (see FIG. **5**). Transform unit **300** may include one or more matrix memories **300***b* for storing matrices used in transformation processing **300***a*. Transform unit **300** transforms incoming geometry per vertex from object space to screen space; and transforms incoming texture coordinates and computes projective texture coordinates (**300***c*). Transform unit **300** may also perform polygon clipping/culling **300***d*. Lighting processing **300***e* also performed by transform unit **300***b* provides per vertex lighting computations for up to eight independent lights in one example embodiment. Transform unit **300** can also perform texture coordinate generation (**300***c*) for embossed type bump mapping effects, as well as polygon clipping/culling operations (**300***d*).

Setup/rasterizer **400** includes a setup unit which receives vertex data from transform unit **300** and sends triangle setup information to one or more rasterizer units (**400***b*) performing edge rasterization, texture coordinate rasterization and color rasterization.

Texture unit **500** (which may include an on-chip texture memory (TMEM) **502**) performs various tasks related to texturing including for example:

- retrieving textures **504** from main memory **112**,
- texture processing (**500***a*) including, for example, multi-texture handling, post-cache texture decompression, texture filtering, embossing, shadows and lighting through the use of projective textures, and BLIT with alpha transparency and depth,
- bump map processing for computing texture coordinate displacements for bump mapping, pseudo texture and texture tiling effects (**500***b*), and indirect texture processing (**500***c*).

Texture unit **500** outputs filtered texture values to the texture environment unit **600** for texture environment processing (**600***a*). Texture environment unit **600** blends polygon and texture color/alpha/depth, and can also perform texture fog processing (**600***b*) to achieve inverse range based fog effects. Texture environment unit **600** can provide multiple stages to perform a variety of other interesting environment-related functions based for example on color/alpha modulation, embossing, detail texturing, texture swapping, clamping, and depth blending.

Pixel engine **700** performs depth (z) compare (**700***a*) and pixel blending (**700***b*). In this example, pixel engine **700** stores data into an embedded (on-chip) frame buffer memory **702**. Graphics pipeline **180** may include one or more embedded DRAM memories **702** to store frame buffer and/or texture information locally. Z compares **700***a'* can also be performed at an earlier stage in the graphics pipeline **180** depending on the rendering mode currently in effect (e.g., z compares can be performed earlier if alpha blending is not required). The pixel engine **700** includes a copy operation **700***c* that periodically writes on-chip frame buffer **702** to main memory **112** for access by display/video interface unit **164**. This copy operation **700***c* can also be used to copy embedded frame buffer **702** contents to textures in the main memory **112** for dynamic texture synthesis effects. Antialiasing and other filtering can be performed during the copy-out operation. The frame buffer output of graphics pipeline **180** (which is ultimately stored in main memory **112**) is read each frame by display/video interface unit **164**. Display controller/video interface **164** provides digital RGB pixel values for display on display **102**.

Example Achromatic Lighting Function

As discussed above, transform unit **300** in the example embodiment performs lighting in addition to geometric transformations, clipping, culling and other functions. In the example embodiment, transform unit **300** supports lighting in hardware as a per-vertex calculation. This means that a color (RGB) value can be computed for every lit vertex, and that these colors can be linearly interpolated over the surface of each lit triangle. This is known as Gouraud shading. Additional details concerning an example lighting implementation are discussed below in connection with FIGS. **12** and following.

The example embodiment transform unit **300** provides an additional use for lighting function(s) **302** not available in traditional graphics systems. Generally, the output of the lighting function in the traditional graphics system is a color used for polygon shading. Some graphics systems provide an alpha (e.g., transparency) value based on a lighting function. In the example embodiment provided by the present invention, a lighting function is used to provide an achromatic parameter (i.e., neither color nor alpha, but something else) used to subsequently modify a color and/or opacity.

FIG. **6** is a block diagram showing such an arrangement where lighting function **302** provides an achromatic parameter used by a subsequent process **304** to modify a color or opacity. The results of the modification are displayed on a display device such as display **56**. In this context, the term "lighting function" generally means a mathematical function of a surface position, a surface orientation, an eye location and, in some cases, a light location. Lighting functions can be defined as any combination of these coordinates.

In the example embodiment, the achromatic parameter outputted by lighting function **302** is processed by a texturing function **306** as shown in FIG. **7**. At a very simple level, texturing an object means "glueing" an image onto that object. In more detail, texturing generally works by modifying the values used in lighting function **302**. For example, in the typical case, a lighting function **302** is used to determine the color and illumination of a polygon surface, and a texturing function is used to modify that color/illumination to provide an additional effect (e.g., to create the appearance of a brick wall or a wood-grain, to make the surface appear bumpy, mirrored or warped, etc.). In the example embodiment shown in FIG. **7**, in contrast, the output of lighting function **302** is not a color or transparency value, but is instead a generalized parameter (for example, a texture coordinate) for texturing function **306**. The texturing function develops color and/or opacity information used to modify (e.g., blend) with a primitive color and/or opacity for display on display device **56**.

FIG. **8**A shows an example texture function **306**. In this example, the lighting function **302** produces an achromatic output parameter S that parameterizes the example texture function **306**. In this FIG. **8**A example, the example texture function **306** selects one of three colors (C1, C2, C3) or opacities depending upon the value of parameter S. Thus, the particular color or opacity outputted by texture function **306** is determined as a function of the parameter S outputted by lighting function **302**. Because lighting function **302** is providing parameter S, the selection of which color or opacity outputted by texture function **306** can depend on any of various factors used by the lighting function calculation, including for example:

distance,

attenuation,

angle,

vector,

cosine,

polynomial,

light source type,

other coefficient.

While texture function **306** may be implemented in a variety of different ways, a cost-effective approach is to store the texture function **306** output values in a texture lookup table or map and to access those values using texture coordinates. FIG. **8**B shows an example one-dimensional texture map **308** indexed by lighting function **302** output parameter S. An advantage of using a conventional texture mapping function in the example embodiment is that texture mapping hardware or other functionality available for general purpose texturing can also be used to implement texture function **306** in cooperation with lighting function **302**.

FIG. **9** shows a more detailed example including a two-dimensional texture mapping operation **306**. In this example, a lighting calculation **302** is performed based on an identification of vertices and lighting definitions. The output of lighting calculation **302** in the example embodiment comprises per-vertex colors (e.g., red, green, blue) and/or transparency (i.e., alpha). The example embodiment typically uses these lighting calculation **302** color outputs for Gouraud shading of a polygon surface. However, in this mode of operation, one of the color channels (e.g., blue) is discarded, and the other two color channels (i.e., red, green) are converted into texture coordinates s, t using a conversion operation **308**. The texture coordinates s, t are applied to one or more texture mapping operations **306***a*, **306***b*, etc. to provide color/transparency output texels. Blending operation **602** may blend these texels with surface color information (which may be derived using conventional shading techniques based on the same or different lighting calculation) to provide shaded, textured polygons for display.

In the example embodiment, texture mapping operation **306** provides two-dimensional texture mapping as shown in FIG. **10**A. In this example, the t texture coordinate is generated based on the green color channel output of lighting calculation **302**, and is used to select one of n one-dimensional texture maps within a two-dimensional texture map **310**. The other texture coordinate s is developed based on the red color channel output of lighting calculation **302**, and is used to select a particular texel within the one-dimensional texture selected by the t coordinate. Of course, the s texture coordinate could select the 1-D map and the t texture coordinate could select a particular texel in other implementations, and/or different colors and/or opacities could be used to generate the different texture coordinates. Three texture coordinates could be used to select texels in a 3D texture if desired.

FIG. **10**B is an illustrative example of a two-dimensional texture map **310** comprising a number of one-dimensional texture maps **308**. The particular two-dimensional texture map shown in FIG. **10**B is particularly suitable for cartoon lighting effects. The example shown includes a number of one-dimensional texture maps including four maps **308(1)** . . . **308(4)** each comprising two different kinds of texels (e.g., purple texels and blue texels). One of the texture coordinates (e.g., t) selects between these different texture maps and the other texture coordinate (e.g., s) selects a particular texel (i.e., blue or purple). The various 1D texture maps **308(1)** . . . **308(4)** provide different mappings between the texture coordinates and blue or purple texels to provide different brush strokes or other effects.

As another example, the 1D texture map **308(6)** shown in FIG. **10**B includes four different types of texels (yellow, orange, red and brown). These different colors could be used to provide bold cartoon-like lighting effects where, for example, the angle a directional light makes with an object or the distance of an object from a light source determines the color resulting from the output of texture mapping operation **306**. Such visualization can have a variety of interesting applications—especially in non-photorealistic real time rendering such as dynamically-generated cartoon animation. For example, it is possible to define a virtual cartoon light which lights up an object. The object's rendered visualization becomes dependent on vertex position, the local cartoon light position and other factors the lighting calculation **302** takes into account (e.g., specular or diffuse computation, distance attenuation, etc.). In one example, it is possible to set the red color channel to zero and allow the lighting calculation **302** to compute the green channel to specify a particular texel value within a 1D texture defining a set of brush strokes. The material color main processor **110** typically can apply to lighting calculation **302** can be used to specify which 1D texture to select within a 2D texture map. Lighting calculation **302** calculates which brush stroke to select on a vertex-by-vertex basis at no extra cost beyond supplying one index per vertex.

While the example shown in FIG. **9** is particularly useful for cartoon lighting, it can also be used for many other applications. As one example, lighting function **302** can be used to calculate a shadow volume or surface. Lighting calculation **302** based on a given vertex could generate a shadow volume defined at texture coordinates used for the texture mapping operation **306**. Many other applications are possible. For example, one interesting application relates to projective textures. An undesirable property of projective textures is that they typically project forward and backward from the camera. The techniques disclosed herein can provide projective texture coordinate generation based on a lighting function which provides attenuation (e.g., to eliminate backwards facing lighting) and/or distance attenuation (e.g., to attenuate the projective texture based on how far it is projected—just as you might see when using a real slide projector to project an image. Such projective texturing in combination with the achromatic lighting function described herein can produce many interesting images and imaging effects.

A conversion operation **306** as shown in FIG. **9** may not be necessary in all implementations. In the example embodiment, lighting calculation **302** generates an integer output that conversion block **308** converts into a floating point representation suitable for texture coordinates used in the following texture mapping operation **306**. However, such integer-to-floating point conversion would not be necessary in other implementations, or other implementations could use different types of conversions as desired.

In the example embodiment shown in FIG. **9**, lighting calculation **302** need not calculate both s and t texture coordinates. Since only one texture coordinate is used as a parameter in the example embodiment to select which particular texel was in a one-dimensional texture map should be applied to a primitive surface, the preferred embodiment preferably calculates that texture coordinate (or in intermediate value from which that texture coordinate is derived) using lighting calculation **302**. However, depending on the application, it might be desirable for the application program as opposed to lighting calculation **302** to specify another texture coordinate used to select (in this example embodiment) between plural one-dimensional textures **308**. As one example, the application program running on main processor **110** can specify a value for any or all of the color channel outputs of lighting calculation **302** via the lighting definitions applied to the lighting calculation input. In some applications, it may be desirable for the main processor **110** to specify the contents of, for example, the green color channel and thus the particular one-dimensional texture used in the texture mapping operation **306**. This provides additional application programmer control while still allowing the lighting calculation **302** to dynamically generate the s texture coordinate based on the variables lighting calculation unit **302** evaluates. Floating point values the main processor **110** sends to transform unit **300** can be truncated to RGB8 to allow calculations to occur in higher precision.

In the example embodiment, there is no reason why lighting calculation **302** cannot produce a negative output value. In the example shown in FIG. **9**, this corresponds to backlighting an object. Thus, it is possible to have negative or backlit cartoon lighting in the example embodiment. This could be useful to provide effects where there is information on the backside of an object. In the preferred embodiment, the lighting unit always outputs a positive color (value). The preferred embodiment supports a negative type of lighting calculation, but it up to the application to add a scale and/or a bias so that the final value ends up being positive. For example, the output of the lighting calculation could be mapped from −1 to 0 and from +1 to 1 before being converted to a texture coordinate(s). The example embodiment does not clamp negative values, but simply maps them into positive numerical values—with the application being careful to ensure that these positive values are interpreted appropriately. Of course, other implementations could support negative lighting values directly if desired.

Texture mapping operation **306** and blending operation **602** shown in FIG. **9** can be arbitrarily complex. For example, it is possible to blend with alpha. As another example, it will be possible to use two separate color channels outputted by lighting calculation **302** for two different texture mapping operations which could then be blended together by blender **602**. Since texture mapper **500** and texture environment unit **600** in the example embodiment are both multi-task/multi-stage operations, a sequence of direct/indirect operations can be provided based on the output of lighting calculation **302** to provide a variety of interesting and complicated effects. See, for example, commonly assigned copending provisional application No. 60/226,891, filed Aug. 23, 2000 and its corresponding utility application No. 09/722,382, filed Nov. 28, 2000, both entitled "Method And Apparatus For Direct And Indirect Texture Processing In A Graphics System", and commonly assigned copending provisional application No. 60/226,888, filed Aug. 23, 2000 and its corresponding utility application No. 09/722,367, filed Nov. 28, 2000, both entitled "Recirculating Shade Tree Blender For A Graphics System", all of which are incorporated by reference herein.

Example Lighting Pipeline Implementation

FIG. **11** shows an example block diagram of lighting calculation **302**. In this example, lighting calculation **302** is performed by transform unit **300** in response to information received from command processor **200**. This information can come from a variety of sources including main processor **110** and main memory **112** (see FIG. **4**).

In the example embodiment, the transform unit **300** includes a master control section **320**, a lighting computation pipeline **322**, an accumulator **324** and—for purposes of texture generation, an integer-to-floating point converter **308**. Master controller **320** receives lighting definitions and vertex definitions from command processor **200** and, after appropriate storage/buffering, provides associated information to the lighting computation pipeline **322**. Lighting pipeline **322** performs a lighting computation in the following basic form:

$$C_n = C_{material}\left[A_c + \sum_{i=0} L(c)\cdot A\right]$$

where C_n defines the output of the lighting calculation pipeline, $C_{material}$ defines the material color, A_c defines the ambient color, L(c) defines the lighting diffuse or specular component, and A defines distance attenuation. This calculation computes an RGB triplet since the example embodiment lighting calculation pipeline **322** can perform two such lighting calculations in parallel. Because of this parallel computation feature, one of the lighting computations can be used for achromatic lighting effects for an object and the other lighting computation can be used for chromatic lighting effects on the same object. The parallel computation feature makes effects such as cartoon lighting "free" in the sense that it takes no more processing time to generate a shaded polygon surface with cartoon lighting effects than it does to generate the shaded polygon surface without such cartoon lighting effects. In the example embodiment, the C_n value generated by lighting computation pipeline **322** can be positive or negative—with negative lighting allowing back-lit and other interesting effects.

In the example embodiment, a C_n output of lighting computation pipeline **322** is accumulated by a integer accumulator **324**. The accumulated output is, in the example embodiment, converted into floating point by conversion block **308** and provided as texture coordinates to texture unit **502** for texture mapping operations. The example embodiment can provide texture filtering as part of texture mapping operation **306**. The application programmer should be careful about the texture filtering mode chosen when using lighting calculation **302** to generate texture coordinates. Problems may result due to the fact that the s and t axes in the example embodiment are used for independent factors, but certain types of texture filtering apply to both axes simultaneously. One work around is to duplicate, within the texture map, each entry along the t axis in order to ensure that interpolation between adjacent t values has no effect on the final output. Thus, one-dimensional texture filtering for adjacent values of t will be identical. Mipmap filtering with multiple levels of details can also take place, but this may also act to reduce the number of 1D textures within a given 2D texture map.

In the example embodiment, another complication results from the method of converting the lighting calculation **302** color value into texture coordinates. The color value produced by lighting calculation **302** in the example implementation is an 8-bit integer in the range of 0–255. Convert block **308** converts this integer value into a floating point number by dividing it by 255. However, the value is converted into a texture coordinate by multiplying it by the texture size in

the example embodiment. This process means that the application programmer should pay careful attention to the texture coordinate for choosing the 1D texture. Assuming a texture size of 256 and GX_NEAR texture filtering, this will map in manner:

Color Value	Converted texture coordinate	Nearest value
0	0	0
64	64.251	64
127	127.498	127
128	128.502	129
192	192.753	193
254	254.996	255
255	256	255

Due to the conversion process, coordinate value 128 is skipped, and color values 254 and 255 map to the same coordinate value. If we assume a texture size of 256 and GX_LINEAR filtering, we have the following mappings:

Color Value	Converted texture coordinate	Coords looked up
0	−0.5	0, 0
1	0.504	0, 1
2	1.508	1, 2
3	2.512	2, 3
4	3.516	3, 4
126	125.994	125, 126
127	126.998	126, 127
128	128.002	128, 129
253	253.492	253, 254
254	254.496	254, 255
255	255.5	255, 255

It is safe to use n*2 to convert a table 1D into a color value in the example implementation. However, the 1D textures should be stored in a non-straightforward manner within the 2D texture. The table for n=0 should be stored at coordinate 0 (only), tables for n=1 to n=63 should be stored at n*2−1 and n*2, and tables for n=64 to n=127 should be stored at n*2 and n*2+1. Coordinate **127** may be left empty since it will not normally be accessed in this particular implementation. Other implementations might avoid this issue altogether, or present different conversion issues.

Example More Detailed Transform Unit 300 Description

FIGS. **12**–**20** show a further example, more detailed embodiment of transform unit **300** including a lighting pipeline used for lighting calculation **302**. In the example embodiment of system **50**, transform unit **300** supports lighting in hardware as a per-vertex calculation. This means that a color (RGB) value can be computed for every lit vertex, and that these colors can be linearly interpolated over the surface of each lit triangle (known as Gouraud shading). Transform unit **300** in this example embodiment has full support for diffuse local spotlights, and also has some support for infinite specular lighting.

Transform unit **300** in this example embodiment supports diffuse attenuation. This means that the front of the object can be brighter than the sides, and the back darkest. Transform unit **300** supports vertex normals so as to provide diffuse attenuation. For each vertex, the vertex normal (N) is compared against the vector between the vertex and the light position.

The example embodiment of transform unit **300** also supports local lights. Local lights have a position within the world and possibly also a direction. Each light is defined to have a position. Using the position of each vertex and the position the light, transform unit **300** can perform per-vertex distance attenuation. This means you can make the brightness of the light shining on an object decrease as the object moves away from the light.

Transform unit **300** in the example embodiment also supports directional lighting. Support ranges non-directional lights, to subtle directional effects, to highly directional spotlights. These effects are supported by angle attenuation. Thus, vertices directly "in the beam" of the light can be made brighter than vertices outside of the beam or behind the light.

Local diffuse lights can be both distance-attenuated and angle-attenuated. By programming the proper lighting equation, it is possible for an application programmer to obtain attenuation values as an output color or alpha (or, in the case of texture coordinate generation, as a texture coordinate).

In the example implementation, transform unit supports eight physical lights. The application programmer can describe the attenuation parameters, position, direction and color of each light. The application programmer can also control up to four physical color channels that accumulate the result of the lighting equation. By associating lights with channels, the application programmer can choose to sum the effect of multiple lights per vertex, or combine them later in the texture environment unit **600**. The number of channels available to the texture environment unit **600** is set by the application programmer. In some cases (e.g., when using a color channel to generate texture coordinates), a light channel is computed but not outputted as a color or opacity. As discussed above, transform unit **300** is pipelined so as calculate two color channels simultaneously, but may provide only one color channel directly to texture environment unit **600** for blending. The other color channel can be provided in the form of texture coordinates to texture unit **500**.

Each color channel enables attenuation in the selection of color source. A light mask associates up to eight lights with the channel. See FIG. **12** channel which shows example association of up to eight different lights with any of two color channels and two alpha channels to provide two independent outputs one of which can be converted to texture coordinates.

As shown in FIG. **12**, transform unit **300** in the example embodiment generates two RGBA colors (color **0** and color **1**). Each output color has two lighting functions: one for RGB and one for alpha, for a total of four lighting functions per polygon per vertex. Four such lights allow a variety of lighting effects such as, for example, in multitexturing. Each function can be comprised of a material color in operations based on a global ambient color and the state of the eight lights retained by transform unit **300**. The equations enable diffuse, specular and spotlight attenuation. The lighting data path is designed to be optimal for local diffuse spotlights in the preferred example embodiment, but it is also possible to generate specular highlights and/or attenuation factors for texture-based lighting with the same data path. As described above, the light colors can also be used to generate texture coordinates.

Example Lighting Calculation

Example lighting equations performed by transform unit **300** are as follows:

$$C = \begin{cases} Material_c \begin{bmatrix} R \\ G \\ B \end{bmatrix} \times LightFunc \begin{bmatrix} R \\ G \\ B \end{bmatrix}, & \text{if } C = Color0_{RGB}, Color1_{RGB} \\ Material_c[A] \times LightFunc_c[A], & \text{if } C = Color0_{Alpha}, Color1_{Alpha} \end{cases}$$

$$Material_c = MaterialSrc_c = REGISTER?\,VertexColor_c : MaterialReg_c$$

$$LightFunc_c = \begin{cases} 1.0, & \text{if } LightFuncEnable_c = \text{FALSE} \\ Illum_c, & \text{if } LightFuncEnable_c = \text{TRUE} \end{cases}$$

$$Illum_c = Clamp\left(Amb_c + SignedInt\left(\sum_{i-0}^{i-7} Enable_c(i) Atten_c(i) DiffuseAtten_c(i) Color_i \right)\right)$$

$$Amb_c = \left(AmbSrc_c = REGISTER?\,VertexColor_c : AmbientReg \right)$$

In the example embodiment, the material and global ambient colors can come from a register or in the form of a vertex color from command processor **200**. An application requiring more than eight lights can compute the illumination from the additional lights, based on software executing on main processor **110**, so that the result is one of the vertex colors, and set the ambient source register to use that vertex color. It is also possible if desired for main processor **110** to compute any or all of the lighting calculations using software and provide those resulting computation outputs in the form of vertex colors to transform unit **300** for conversion into texture coordinates; or the main processor may pass the computed texture coordinates to texture unit **500** for purposes of texture mapping.

Disabling the "LightFunc" parameter passes the material color through transform unit **300** unchanged. This can be used to allow main processor **110** to directly select, based on application program software control, which of a plurality 1D textures to use in a texture mapping operation responsive to an achromatic lighting function output.

Any or all of the available eight lights can be enabled in each lighting function. The sum of the per-light illumination is clamped to [−1, 1] in the example embodiment, and converted to integer 2's complement before adding the global ambient term. Since the total illumination is clamped to [0, 1], a material cannot become brighter through lighting in the example embodiment. If this effect is desired, the light colors can be premultiplied by the material color, and the material color in the equation can be set to 1.0. Other arrangements can be provided in other example implementations to allow materials to become brighter through lighting.

In the example embodiment, the alpha equations can be used when monochrome results are sufficient. The resulting alpha values can be combined with other RGB and alpha values in texture environment unit **600** in the example embodiment. For example, it is possible to put the diffuse result in the color output for the channel **0** color, a specular result in the alpha output of the color **0** channel, and have the texture environment unit **600** multiply the diffuse color by the texture color and add a (e.g., white) specular highlight in a single stage of texture environment unit **600**.

Flexibility is provided in the diffuse attenuation function in the example embodiment, beyond the command (N·H) clamp to [0, 1]. Attenuation can be defeated for lighting equations which do not have a diffuse property or left unclamped. Unclamped dot products allow light-based texture generation to control illumination for 180°. Since the illumination will be clamped in the example embodiment, signed lighting functions may be scaled and biased appropriately using color_c and amb_c. The example embodiment provides three example diffuse attenuation functions a lighting equation can use:

$$DiffuseAtten_c(i) = \begin{cases} 1.0, & \text{if } DiffAttenSelect_c = \text{NONE} \\ \hat{N}\cdot\hat{L}_i, & \text{if } DiffAttenSelect_c = \text{SIGNED (if SPOTLIGHT only)} \\ Clamp0(\hat{N}\cdot\hat{L}_i), & \text{if } DiffAttenSelect_c = \text{CLAMP (if SPOTLIGHT only)} \end{cases}$$

The angle attenuation logic in the example embodiment computes a second-order polynomial based on the dot product of the light-to-vertex vector and the light-direction vector. A sharp fall off is achieved by extrapolating the squared and linear terms. Clamping is used to avoid negative values produced by extrapolation for angles outside of a spotlight angle. Range attenuation can be performed by the inverse of another second-order polynomial. The distance value, d, is the length of the vector from the vertex to the light position. A light equation with only distance attenuation can be used for texture-based lights to simulate the distance-based illumination falloff of projected or other textures.

This same logic can be used to approximate common specular attenuation, $(N\cdot H)^5$ for a parallel light source. The light-to-vertex and light-direction vectors may be replaced with the normal and half-angle vectors respectively. Attenuation can be defeated in a lighting function to permit non-attenuated point light (e.g., omni-direction) sources to be used in both a diffuse and specular equation. In this example, the light's angle attenuation coefficients may be used for the specular equation, and attenuation is turned off in the diffuse equation. Specular and diffuse equations in the example embodiment are combined in texture environment **600** as opposed to within transform unit **300** in the example embodiment, but other implementations are possible.

Further details of the example attenuation function are as follows:

$$Atten_c = AttenEnable_c\,?\,\frac{Clamp0(a_{2_i}AAtt_c(i)^2 + A_{1_i}AAtt_c(i) + A_{o_i})}{K_{2_i}d_c^2(i) + k_{1_i}d_c(i) + k_{0_i}}:1.0$$

$$AAtt_c(i) = \begin{cases} \hat{N}\cdot\hat{L} > 0\,?\,clamp0(\hat{N}\cdot H_i):0, & \text{if } AttenSelect_c = \text{SPECULAR} \\ clamp0(\hat{L}\cdot L_{dir_i}), & \text{if } AttenSelect_c = \text{SPOTLIGHT} \end{cases}$$

$$d_c(i) = \begin{cases} \hat{N}\cdot\hat{L} > 0\,?\,clamp0(\hat{N}\cdot H_i):0, & \text{if } AttenSelect_c = \text{SPECULAR} \\ \sqrt{L_i\cdot L_i}, & \text{if } AttenSelect_c = \text{SPOTLIGHT} \end{cases}$$

Example Transform Unit **300** Implementation Block Diagram

FIG. **13** is a block diagram of an example implementation of transform unit **300** of system **50**. Transform unit **300** in this example embodiment includes three main sections:

top-of-pipeline section **330**,

light section **332**,

bottom-of-pipeline section **334**.

The top-of-pipeline section **330** in the example embodiment includes light section **332**, a context matrix store **336**, an input FIFO buffer **338**, a dot product unit **340**, a projection block **342**, a texture dot two block **346**, a cripping detector **348**, and a bypass FIFO block **350**. In the example embodiment, top-of-pipeline (TOP) section **330** performs the following example functions:

vertex transform (3 dot products),

Normal transform (3 dot products),

texture transform (2 or 3 dot products for texture),

projection transform (simplified 3 dot products); and light section **332** performs the following example color channel functions:

color channel **0** diffuse computation (1 dot product N·L),

color channel **0** diffuse computation (1 dot product L^2 per light),

color channel **0** diffuse computation (1 dot product N^2).

In addition, the input FIFO receives per-vertex vertex descriptors specifying, for example, the following information:

geometry information XYZ,

Normal vector information N_x, N_y, N_z,

RGBA color 0 per vertex,

RGBA color 1 per vertex,

Binormal vector T_x, T_y, T_z,

Binormal vector B_x' B_y, B_z

Texture 0 data T_0,

Texture 1 to n data S_n, T_n.

Appropriate per-vertex information is provided to light section **332** to enable the lighting computations.

Light section **332** in the example embodiment shown in FIG. **13** includes a lighting parameters memory **352**, a Normal memory **354** and a light data path **356**.

Light parameter memory **352** stores various light parameters used by light data path **356**. Light parameter store **352** thus holds all of the various lighting information (e.g., light vectors, light parameters, etc.). Both global state and ambient state are stored in this memory in the example embodiment. In the example embodiment, each word is written in 32-bits, but only the twenty most significant bits are kept. Each location is three words wide, with minimum word write size of three words in the example embodiment. The following shows example contents of light parameter memory **352**:

Register Address	Definition	Configuration
0/0600	Reserved	
0x0601	Reserved	
0x0602	Reserved	
0x0603	Light0	32b: RGBA (8b/comp)
0x0604	Light0A0	20b: cos atten. A_0
0x0605	Light0A1	20b: cos atten. A_1
0x0606	Light0A2	20b: cos atten. A_2
0x0607	Light0K0	20b: dist atten. K_0
0x0608	Light0K1	20b: dist atten. K_1
0x0609	Light0K2	20b: dist atten. K_2
0x060a	Light0Lpx	20b: x light pos, or inf 1dir x
0x060b	Light0Lpy	20b: y light pos, or inf 1diry y
0x060c	Light0Lpz	20b: z light pos, or inf 1dir z
0x060d	Light0Dx/Hx	20b: light dir x, or 1/2 angle x
0x060e	Light0Dy/Hy	20b: light dir y, or 1/2 angle y
0x060f	Light0Dz/Hz	20b: light dir z, or 1/2 angle z

-continued

Register Address	Definition	Configuration
0x0610-0x067f	Light(n)data	See Light0 data
0x0680-0x07ff	Not used	Reserved

An overview of the light section **332** of the example embodiment is shown in FIG. **14**. Briefly, the light section **332** performs the following local lighting computations:

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = Material_0 \begin{bmatrix} Mr \\ Mg \\ Mb \end{bmatrix}$$

$$\left(Ambient_0 \begin{bmatrix} Ra \\ Ga \\ Ba \end{bmatrix} + \frac{CosAtFunc_0}{DistAtFunc_0} Clamp(Normal \cdot Light_i) \times Diffuse_i \begin{bmatrix} Rd \\ Gd \\ Bd \\ 0.0 \end{bmatrix} \right)$$

This requires a local light vector computation per vertex:

$$Light_i = Normalized \left(LightPos_i \begin{bmatrix} Lx \\ Ly \\ Lz \end{bmatrix} - EyeSpaceVertex \begin{bmatrix} Xh \\ Yh \\ Zh \end{bmatrix} \right)$$

after which, we need to compute:

DifiuseAtten$_0$=Conditional__clamp__to__0(Light$_i$·EyeSpaceNormal)

Thus, the diffuse attenuation calculation requires the light vector and the eye-space Normal. Clamping to 0 may be conditional on an internal flag (e.g., it can be clamped to 1.0 or not clamped at all) in the example implementation. It is possible to allow diffuse lights to have negative dot products. A lighting dot product unit can compute the eye-space Normal while the transform dot product unit computes the geometry eye-space conversion. Then, a lighting dot product unit can compute the N·L, L2 and N^2 dot products. After this, the example embodiment normalizes the results to provide normalized light vector Normal information. After normalization, the intermediate results of the normalization (e.g., distance squared and distance and cosine N·L) are used to compute the attenuation equations as well as the normalization factors. Then, the light ambient vector is multiplied. The resulting triplet is the per-light attenuated diffuse component. This is converted to 2's complement integer, and the resulting three values are accumulated in an integer accumulator. This accumulator adds the ambient terms and any other diffuse terms from other lights. The final sum is then the per-vertex color (in the example embodiment, an 8-bit RGB format clamped to 0 to 255).

FIG. **15** shows an example diagram of the vector dot/Madd block **357** shown in FIG. **14**. If the same dot product unit is used to compute the transform N and all other dot products, then the performances may become somewhat degraded and the scheduling of light becomes difficult since each light needs to re-use the same data path element multiple times. This may lead to complex control issues. To simplify the design, we can implement a second limited dot product unit to separate the various computations. The first dot product unit may compute the transform normal while the other dot product unit computes the vertex transformation. A vector add may then compute the light vector for local lighting. The second dot product may compute N^2, L^2, N·L and N·H (for specular lights). This can be achieved in the example embodiment in a fully pipelined way with no feedbacks. See FIG. **15**.

FIG. **16** shows an example implementation of the normalizer **360** shown in FIG. **14**. Once the lighting vector values are computed, the example embodiment normalizes the results and computes attenuation. Example embodiment normalizer **360** accepts the following inputs:

Cosine attenuation: L·Dir, 1/sqrt (L)

Distance attenuation: L^2, L

Diffuse factor: N·L, N^2, L^2, and computes distance attenuation using the following step performed by example normalizer **360** shown in FIG. **16**:

1. Compute K_2d^2
2. Compute $K_2d^2{}_{+K0}$
3. Compute d
4. Compute K_1d
5. Compute $D_2D^2+K_1d+KO$
6. Compute $1/(K_2d^2+K_1d+K$**0**)

FIG. **17** shows an example distance attenuation unit **362**. The example distance attenuator implementation **362** computes cosine attenuation using the following example steps:

1. Compute Cos=Clamp0(L.Ldir)
2. Compute Cos_2
3. Compute A_2Cos^2
4. Compute A_1Cos
5. Compute A_1Cos+A**0**
6. Compute $A_2Cos^2+A_1Cos+A$**0**
7. Compute Clamp__0(A+2+Cos^2+A$_1$Cos+A**0**)

FIG. **18** shows an example implementation of light scaler **364** that computes the following:

1/sqrt (N^2)

1/sqrt (L^2)

N·L (sqrt (N^2)×sqrt(L^2)).

Some of the units (e.g., 1/sqrt and some of the multipliers) can be shared among the various data path implementations shown in FIGS. **15**–**18**. Thus,.an implementation might approximately-require on the order of eighteen multipliers and ten adders. Inversion and 1/sqrt can be performed using a table lookup or a simple one-pass Newton-Raphson interpolator or some other pipeline interpolator. Alpha and specular writing computations do not require any additional hardware in the example embodiment since they are just changes in the lighting equation.

FIG. **19** shows an example integer accumulator **336** implementation. When a new attribute arrives for each color, that color is accumulated. Once all lights are accumulated for a color, and the ambient is added (e.g.; from the vertex color FIFO or from a register) then the material color is multiplied. The final RGB/A color is then accumulated into an accumulation/format register by construction of the final color and texture generation. Once the color/texture is computed, it is then written into an output FIFO. Control may follow these general guidelines:

```
If (new attribute = = new light for color X)
    Accumulate new light into color X
    Increment number of lights for color X
```

-continued

```
End
If (number of lights for color X is maximum)
    Transfer color to multiplier
    Perform material multiply
End
If (color X is in multiply state)
    Accumulate color X first
End
If (Accumulation of color X is complete (RGBX or AXX or RGBA))
    Format color X for color, if color enabled
    Format color X for texture, if texture enabled and color disabled or
    color already loaded
    Load output fifo with formatted data, increment color/texture count
End
If (color count and texture count at maximum)
    Write data to BOP
    Pop fifo
End
```

FIG. **20** shows an example stage transition diagram used to control light pipeline **332** in the example embodiment. Arbiter logic decides the sequence .of events that it issued into the light data path. The example embodiment arbiter can only issue a new event every four or eight cycles, depending on the event. The list of possible events includes:

light computation for a specific color/alpha,

bump map computation.

For the above events, the arbiter drops an attribute into the control pipeline every 4/8 cycles. Each of these attribute carries the execution instructions for the event into the light pipeline **332**. At the end of the pipeline, the attributes are used to increment local counts which are used to determine if the colors/textures are complete.

The following shows example control registers used to control how transform unit **300** behaves, treats data and textures, etc.:

Register Address	Definition	Configuration
0x1000	Error	
0x1001	Diagnostics	
0x1002	State0	Internal state register0
0x1003	State1	Internal state register1
0x1004	Xf_clock	Enables power saving mode 0: No power saving when idle 1: Enable power saving when idle
0x 1005	ClipDisable	Disables some or all of clipping B[0]: When set, disables clipping detection (0 default) B[1]: When set, disables trivial rejection (0 default) B[2]: When set, disables cpoly clipping acceleration (0 default)
0x1006	Perf0	Performance monitor selects
0x1007	Perf1	Xform target performance register: [6:0]: Xform internal target performance (Cycles/vertex)
0x1008	InVertexSpec	B[1:0]: Specifies host supplied color0 usage: 0: No host supplied color information 1: Host supplied color0 2: Host supplied color0 and color1 B[3:2]: Specifies host supplied normal: 0: No host supplied normal 1: Host supplied normal 2: Host supplied normal and binormals B[7:4]: Specifies # of host supplied texture coordinates 0: No host supplied textures 1: 1 host supplied texture pair (S0, T0) 2-8: 2-8 host supplied texturepairs 9-15: Reserved
0x1009	NumColors	Specifies the number of colors to output: 0: No xform colors active 1: Xform supplies 1 color (host supplied or computed) 2: Xform supplies 2 colors (host supplied or computed)
0x100a	Ambient0	32b: RGBA (8b/comp) Ambient color0 specifications
0x100b	Ambient1	32b: RGBA (8b/comp) Ambient color1 specifications
0x100c	Material 0	32b: RGBA (8b/comp) global color0 material specifications
0x100d	Material 1	32b: RGBF (8b/comp) global color1 material specification
0x100e	Color0Cntrl	B[0]: Color0 Material source 0: Use register (Material 0) 1: Use CP supplied Vertex color 0 B[1]: Color0 LightFunc 0: Use 1.0 1: Use Illum0 B[2]: Light0 is source 0: Do not use light 1: Use light B[3]: Light1 is source 0: Do not use light 1: Use light B[4]: Light2 is source 0: Do not use light 1: Use light B[5]: Light3 is source 0: Do not use light 1: Use light B[6]: Ambient source 0: Use register Ambient0 register 1: Use CP supplied vertex color 0 B[8:7]: DiffuseAtten function 0: Select 1.0 1: Select N.L, signed 2: Select N.L clamped to [0,1.0] B[9]: AttenEnable function 0: Select 1.0 1: Select Attenuation fraction B[10]: AttenSelect function 0: Select specular (N.H) attenuation 1: Select diffuse spotlight (L.Ldir) attenuation B[11]: Light4 is source 0: Do not use Light 1: Use light B[12]: Light 5 is source 0: Do not use Light 1: Use light B[13]: Light 6 is source 0: Do not use Light 1: Use light B[14]: Light 7 is source 0: Do not use Light 1: Use light
0x100f	Color1Cntrl	B[0]: Color Material source 0: Use register (Material 1) 1: Use CP supplied Vertex color 1 B[l]: Color1 LightFunc 0: Use 1.0 1: Use Illum1 B[2]: Light0 is source 0: Do not use light 1: Use light B[3]: Light1 is source 0: Do not use light 1: Use light B[4]: Light2 is source 0: Do not use light 1: Use light B[5]: Light3 is source 0: Do not use light 1: Use light

-continued

Register Address	Definition	Configuration
		B[6]: Ambient source
		0: Use register Ambient1 register
		1: Use CP supplied vertex color 1
		B[8,7]: DiffuseAtten function
		0: Select 1.0
		1: Select N.L, signed
		2: Select N.L clamped to [0,1.0]
		B[9]: AttenEnable function
		0: Select 1.0
		1: Select Attenuation fraction
		B[10]: AttenSelect function
		0: Select specular (N.H) attenuation
		1: Select diffuse spotlight (L.Ldir) attenuation
		B[11]: Light4 is source
		0: Do not use Light
		1: Use light
		B[12]: Light 5 is source
		0: Do not use light
		1: Use light
		B[13]: Light 6 is source
		0: Do not use light
		1: Use light
		B[14]: Light7 is source
		0: Do not use light
		1: Use light
0x1010	Alpha0Cntrl	B[0]: Color0 alpha Material source
		0: Use register (Material 0 alpha)
		1: Use CP supplied Vertex color 0 alpha
		B[1]: Color0 alpha Light Func
		0: Use 1.0
		1: Use Illum0
		B[2]: Light0 alpha is source
		0: Do not use light
		1: Use light
		B[3]: Light1 alpha is source
		0: Do not use light
		1: Use light
		B[4]: Light2 alpha is source
		0: Do not use light
		1: Use light
		B[5]: Light 3 alpha is source
		0: Do not use light
		1: Use light
		B[6]: Ambient source
		0: Use register Ambient0 alpha register
		1: Use CP supplied vertex color 0 alpha
		B[8:7]: DiffuseAtten function
		0: Select 1.0
		1: Select N.L, signed
		2: Select N.L clamped to [0,1.0]
		B[9]: AttenEnable function
		0: Select 1.0
		1: Select Attenuation fraction
		B[1-]: AttenSelect function
		0: Select specular (N.H) attenuation
		1: Select diffuse spotlight (L.Ldir) attenuation
		B[11]: Light4 is source
		0: Do not use Light
		1:Use light
		B[12]: Light 5 is source
		0: Do not use Light
		1: Use Light
		B[13]: Light 6 is source
		0: Do not use Light
		1: Use light
		B[14]: Light 7 is source
		0: Do not use Light
		1: Use light
0x1011	Alpha1Cntrl	B[0]: Color1 alpha Material source
		0: Use CP supplied Vertex color 1 alpha
		B[I]: Color1 alpha LightFunc
		0: Use 1.0
		1: Use Illum0
		B[2]: Light0 alpha is source
		0: Do not use light
		1: Use light
		B[3]: Light1 alpha is source
		0: Do not use light
		1: Use light
		B[4]: Light2 alpha is source
		0: Do not use light
		1: Use light
		B[5]: Light3 alpha is source
		0: Do not use light
		1: Use light
		B[6]: Ambient source
		0: Use register Ambient1 alpha register
		1: Use CP supplied vertex color 1 alpha
		B[8:7]: DiffuseAtten function
		0: Select 1.0
		1: Select N.L, signed
		2: Select N.L clamped to [0,2.0]
		B[9]: AttenEnable function
		0: Select 1.0
		1: Se]ect Attenuation fraction
		B[10]: AttenSelect function
		0: Select specular (N.H) attenuation
		1: Select diffuse spotlight (L.Ldir) attenuation
		B[11]: Light 4 is source
		0: Do not use Light
		1: Use light
		B[12]: Light 5 is source
		0: Do not use Light
		1: Use light
		B[13]: Light 6 is source
		0: Do not use Light
		1: Use light
		B[14]: Light 7 is source
		0: Do not use Light
		1: Use light
0x1012	DualTexTran	B[0]: When set(1), enables dual transform for all texture coordinates. When reset (0), disables dual texture transform feature [rev B]
0x1018	MatrixIndex0	B[5:0]: Geometry matrix index
		B[11:6]: Tex0 matrix index
		B[17:12]: Tex1 matrix index
		B[23:18]: Tex2 matrix index
		B[29:24]: Tex3 matrix index
0x1019	MatrixIndex1	B[5:0]: Tex4 matrix index
		B[11:6]: Tex5 matrix index
		B[17:12]: Tex6 matrix index
		B[23:18]: Tex7 matrix index
0x101a	ScaleX	Viewport scale X
0x101b	ScaleY	Viewport scale Y
0x101c	ScaleZ	Viewport scale Z
0x101d	OffsetX	Viewport offset X
0x101e	OffsetY	Viewport offset Y
0x101f	OffsetZ	Viewport offset Z
0x1020	ProjectionA	A parameter in projection equations
0x1021	ProjectionB	B parameter in projection equations
0x1022	ProjectionC	C parameter in projectlon equations
0x1023	ProjectionD	D parameter in projection equations
0x1024	ProjectionE	E parameter in projection equations
0x1025	ProjectionF	F parameter in projection equations
0x1026	ProjectOrtho	If set selects orthographic otherwise non-orthographic (Zh or 1.0 select)
0x103f	NumTex	Number of active textures
0x1040	Tex0	B0: Reserved
		B1: texture projection
		0: (s,t): texmul is 2x4
		1: (s,t,q): texmul is 3x4
		B2: input form (format of source input data for regular textures)
		0: (A, B, 1.0, 1.0) (used for regular texture source)
		1: (A, B, C, 1.0) (used for geometry or normal source)
		B3: Reserved
		B[6,4]: texgen type
		0: Regular transformation (transform incoming data)
		1: texgen bump mapping

-continued

Register Address	Definition	Configuration
		2: Color texgen: (s,t)=(r,g:b) (g and b are concatenated), color0 3: Color texgen: (s,t)=(r,g:b) (g and b are concatenated), color 1 B[11:7]: regular texture source row: Specifies location of incoming textures in vertex (row specific) (i.e.: geometry is row0, normal is row1, etc . . .) for regular transformations (refer to the table below) B[14:12]: bump mapping source texture: n: use regular transformed tex(n) for bump mapping source B[17:15]: Bump mapping source light: n: use light #n for bump map direction source (10 to 17)
0x1041	Tex1	See Tex0
0x1042	Tex2	See Tex0
0x1043	Tex3	See Tex0
0x1044	Tex4	See Tex0
0x1045	Tex5	See Tex0
0x1046	Tex6	See Tex0
0x1047	Tex7	See Tex0
0x1050	Dual Tex0	B[5:0]: Indicates which is the base row of the dual transform matrix for regular texture coordinate0. [Rev B] B[7:6]: Not used. B[8]: specifies if texture coordinate should be normalized before send transform.
0x1051	DualTex1	See DualTex0
0x1052	DualTex2	See DualTex0
0x1053	DualTex3	See DualTex0
0x1054	DualTex4	See DualTex0
0x1055	DualTex5	See DualTex0
0x1056	DualTex6	See DualTex0
0x1057	DualTex7	See DualTex0

Example Application Programming Interface

The following are some example API calls relevant to generation of texture coordinates from lighting functions in an example implementation:

GXSetTexCoordGen

Description

Use this function to specify how texture coordinates are generated. Output texture coordinates are usually the result of some transform of an input attribute; either position, normal, or texture coordinate. You can also generate texture coordinates from the output color channel of the per-vertex lighting calculations.

In C-language syntax the texture coordinate generation function would look like this:

dst__coord=func(src__param, mtx);

An example usage of an example API function call is:

```
void GXSetTexCoordGen(
    GXTexCoordID dst__coord,
    GXTexGenType func,
    GXTexGenSrc src__param,
    u32 mtx);
```

The current vertex descriptor as set by GXSetVtxDesc describes the data input to the graphics processor. Using GXSetTexCoordGen, the application can create new output texture coordinates from the input data. The dst__coord parameter is used to give the output texture coordinate a name. This texture coordinate can be bound to a texture using GXSetTevOrder. The function GXSetNumTexGens specifies a consecutive number of texture coordinates, starting at GX__TEXCOORD**0**, that are available to the GXSetTevOrder function.

Input texture coordinates go through the texture coordinate generation hardware. GXInit initializes the hardware (by calling this API) so that all texture coordinates are transformed by the GX__IDENTITY matrix in order to appear as if input coordinates are passed unchanged through to the texture hardware.

The enumeration GXTexMtx defines a default set of texture matrix names that can be supplied as mtx. The matrix names are actually row addresses (4 floats per row) in the matrix memory that indicate the first row of a loaded matrix. Modelview matrices and texture matrices share matrix memory in the example embodiment.

Example: Generating Texture Coordinates From Vertex Lighting Results

This type of texture coordinate generation can be used to create cartoon lighting effects. One of the color channel results is converted into texture coordinates.

GX__TG__SRTG

The s-coordinate is set equal to the 8-bit red component of the channel. The t-coordinate is set equal to the 8-bit green component of the color channel. For cartoon lighting, the s-coordinate will represent the light intensity and is input to an arbitrary 1D texture look-up to convert intensity to color. The t-coordinate is used to represent material color, and is used to select a 1D table from a 2D texture. Texture coordinates generated using the GX__TG__SRTG function should be generated after any coordinates generated by transforms (GX__TG__MTX2×4 or GX__TG__MTX3×4) and the bump map function (GX-TG__BUMP0–3).

The texture which represents the array of 1D intensity-to-color tables should be constructed carefully in the example embodiment. Each table (row) should be duplicated. Since the s- and t-coordinates are generated from 8-bit colors, a maximum texture of 256×256 can be used. For this texture size, there are 127 tables available ((256–1)/2).

An example rule for generating the green channel color which will create a t-coordinate centered properly in the 2-row table is:

```
n=1-D intensity lookup table index (0–126 for a 256×256 texture)
rows=number of rows in the texture, multiple of 2 if ((2*n+1)<((rows–1)/2))
    green=2*n +1
else
    green=2*n
```

EXAMPLE

```
// convert color0 to s,t for 2-D texture lookup, matrix not used GXSetTexCoodGen(GX__TEXCOORD2, GX__TG__SRTG, GX__TG__COLOR0, GX__IDENTITY);
```

Functional Ordering

Texture coordinates are generated in the functional order in the example embodiment: all transforms first (GX__TG__

MTX2×4 or GX_TG_MTX3×4), followed by bump maps (GX_TG_BUMP0–3), followed by texture coordinate generation from lighting (GX_TG_SRTG).

GXSetNumTexGens

Description

This function sets the number of texture coordinates that are generated and available for use in the Texture Environment (TEV) stages. Texture coordinates are generated from input data as described by GXSetTexCoordGen. The generated texture coordinates are linked to specific textures and specific Texture Environment (TEV) stages using GXSetTevOrder.

A consecutive number of texture coordinates may be generated, starting at GX_TEXCOORD**0**. A maximum of 8 texture coordinates may be generated. If nTexGens is set to 0, no texture coordinates will be generated. In this case, at least one color channel must be output, see GXSetNumChans.

Arguments

nTexGens is Number of texture coordinates to generate.

Example Usage:

void GXSetNumTexGens(u**8** nTexGens);

GXSetNumChans

Description

This function sets the number of lighting color channels that are output to the Texture Environment (TEV) stages. Color channels are the mechanism used to compute per-vertex lighting effects. Color channels are controlled using GXSetChanCtrl. Color channels are generally linked to specific Texture Environment (TEV) stages .

This function basically defines the number of per-vertex colors that get rasterized. If nChans is set to 0, then at least one texture coordinate must be generated, see GXSetNumTexGens. If nChans is set to 1, then channel GX_COLOR**0A0** will be rasterized. If nChans is set to 2 (the maximum value), then GX_COLOR**0A0** and GX_COLOR**1A1** will be rasterized.

Arguments

nChans is Number of color channels to rasterize.

Example Usage:

void GXSetNumChans(u**8** nChans);

GXSetChanCtrl

Description

This function sets the lighting controls for a color channel. The color channel can have one or more (up to 8) lights associated with it, set using light_mask. The diff_fn and attn_fn parameters control the lighting equation for all lights associated with this channel. The amb_src and mat_src can be used to select whether the input source colors come from register colors or vertex colors.

When the channel enable is set to GX_FALSE, the material color source (set by mat_src) is passed through as the channel's output color. When the channel enable is GX_TRUE, the output color depends on the settings of the other controls (i.e., the lighting equation). GXInit sets the enable for all channels to GX

FALSE. GXSetChanCtrl configures the lighting channel. To output the result of the channel computation, use the function GXSetNumChans.

Even though channels GX_COLOR**0** and GX_ALPHA**0** are controlled separately for lighting, they are rasterized together as one RGBA color, effectively GX_COLOR**0A0**. The same is true for GX_COLOR1 and GX_ALPHA1—

effectively, they are rasterized as GX_COLOR**1A1** . Since there is only one rasterizer for color in the graphics hardware, the application chooses which color to rasterize for each stage in the Texture Environment (Tev) unit. This is accomplished using the GXSetTevOrder function.

In order to use a vertex color in channel GX_COLOR**1A1**, two colors per vertex are be supplied, i.e. both GX_VA_CLR**0** and GX_VA_CLR**1** are be enabled in the current vertex descriptor. If only GX_VA_CLR**0** or GX_VA_CLR**1** is enabled in the current vertex descriptor, the vertex color is directed to the channel GX_VA_COLOR**0A0**.

When amb_src is set to GX_SRC_REG, the color set by GXSetChanAmbColor is used as the ambient color. When mat_src is GX_SRC_REG, the color set by GXSetChanMatColor is used as the material color.

Arguments

chan	Color channel.
enable	Enable lighting for this color channel if enable = GX_ENABLE.
amb_src	Source for ambient color.
mat_src	Source for material color
light_mask	Lights used in the lighting equation for this channel.
diff_fn	Diffuse function for lighting
attn_fn	Attenuation function for lighting.

Example Usage:

```
void GXSetChanCtrl(
    GXChannelID chan,
    GXBool enable,
    GXColorSrc amb_src,
    GXColorSrc mat_src,
    GXLightID light_mask,
    GXDiffuseFn diff_fn,
    GXAttnFn attn_fn);
```

Example: Local Diffuse Spot Light

This example demonstrates how to configure the GX_COLOR**0** channel to light the vertex color with a local diffuse spot light. The functions GXInitLightPos and GXInitLightDir are used to initialize the light position and direction. The light direction and position are assumed to have been transformed into view space prior to setting the light object. In order to enable diffuse lighting, diff_fn is set to GX_DF_CLAMP. Since this is a spot light, attn_fn is set to GX_AF_SPOT. The type of spot light angle attenuation function is determined by the light, set here by GXInitLightSpot. The distance attenuation function is set using GXInitLightDistAttn.

```
// Assumes vertex will supply color0.
// init light position, direction, atten functions
GxInitLightPosv( &myLightObj, &pos);
GXInitLightDirv( &myLightObj, &dir);
GxInitLightSpot( &myLightObj, 30.0f, GX_SP_COS2);
GXInitLightDistAttn( &myLightObj, 100.0f, 0.5f, GX_DA_GENTLE);
GXLoadLightObjImm( &myLightObj, GX_LIGHT0 );
GXSetChanAmbColor( GX_COLOR0, black);
GXSetChanCtrl(
    GX_COLOR0,
    GX_TRUE,            // enable lighting
    GX_SRC_REG,          // ambient = 0
    GX_SRC_VTX,          // material color
    GX_LIGHT0,
    GX_DF_CLAMP,           // normal diffuse light
    GX_AF_SPOT);          // spot light attenuation
```

-continued

```
// Set number of channels to light
GXSetNumChans( 1 );
```

Example: Specular Light

This example demonstrates how to set up the GX_COLOR**0** channel for specular lighting. The function GXInitSpecularDir is used to set the light direction. The direction must be transformed to view space prior to initializing the light object. Specular lights are considered to be infinitely far away, so a position parameter is not necessary. The angle attenuation and distance attenuation functions are used to approximate an exponential attenuation function for specular lights. Call GXInitLightShininess to control how shiny the lighted material appears (sets the attenuation parameters). The attn_fn is set to GX_AF_SPEC, enabling the specular computation.

```
// Assumes vertex will supply color0.
// init light direction, attn functions
CXInitSpecularDirv( &myLightObj, &dir);
GXInitLightShininess( &myLightObj, 5.0f);
GxLoadLightObjImm( &myLightObj, GX_LIGHT0 );
GXSetChanAmbColor( GX_COLOR0, black );
GXSetChanCtrl(
    GX_COLOR0,
    GX_TRUE,        // enable lighting
    GX_SRC_REG,         // ambient = 0
    GX_SRC_VTX          // material color
    GX_LIGHT0,
    GX_DF_NONE,             // no diffuse light
    GX_AF_SPEC);        // specular light
// Set number of channels to light
GXSetNumChans( 1 );
```

Example: Parallel Directional Diffuse Light

Although the hardware doesn't support parallel directional diffuse lights, it is possible to obtain "almost parallel" lights by putting a light very far away from every objects to be lit. If the light position is very far from an object, all rays can be considered parallel.

```
// prepares large number (a2 pow 20)
#define LARGE_NUMBER 1048576
// light direction on view space
// the 3D vector (dx, dy, dz) is supporsed to be normalized.
f32 dx, dy, dz;
// init light parameters
GXInitLightPos(
    &myLightObj,
    - dx * LARGE_NUMBER,
    - dy * LARGE_NUMBER,
    - dz * LARGE_NUMBER);
GXInitLightColor( &myLightObj, white);
GXLoadLightObjImm( &myLightObj, GX_LIGHT0 );
GXSetChanAmbColor( GX_COLOR0, ambColor);
GXSetChanMatColor( GX_COLOR0, matColor);
GXSetChanCtrl(
    GX_COLOR0,
    GX_TRUE,        // enable lighting
    GX_SRC_REG,         // ambient = black
    GX_SRC_REG,         // material color
    GX_LIGHT0,
    GX_DF_CLAMP,            // normal diffuse light
    GX_AF_NONE );       // no attenuation
// Set number of channels to light
GXSetNumChans( 1 );
```

Light can be Used in Both Diffuse and Specular Channels

Which calculation is performed in a channel, either local-diffuse or specular, is determined by the channel controls. The light (that's associated with the channel) parameters normally are set with one of these computations in mind. For example, the application sets a position and direction for local diffuse lights (used with a diffuse channel) and set only the direction for a specular light (used with a specular channel). However, if the application only needs a directional diffuse light (the light's position is very far away so all the light's rays are considered parallel), then the same light's parameters can be used for both specular and diffuse channels. In this case, initialize the light's parameters using GXInitSpecularDir.

Example: Per-vertex Light With Pre-lighting

This example will add a pre-lit color (e.g., computed by an art tool) supplied as the per-vertex GX_VA_CLR**0** (see GXSetVtxDesc) to the result of a diffuse local light. In this example we want to implement the equation:

lit_clr=pre_lit_clr*(amb_scale+diff_scale*other_atten*lit_color)

The ambient scale defines the minimum amount of pre-lit color when no lights are shining on an object. The sum of amb_scale and diff_scale should equal 1.0, so when the object is in the brightest light, the vertex color is equal to the pre-lit color.

The material color is configured to be the per-vertex color (pre-lit color). The ambient color register is set equal to the amb_scale. The light color is scaled by the diff_scale.

```
//
// Assumes vertex will supply color0 = pre-lit color.
//
GXInitLightColor(
    myLightObj,
    ScaleColor(myLitClr, 0.75)); // diffuse scale
//
// init light position, direction, atten functions
// not shown
GXLoadLightObjImm(
    myLightObj,
    GX_LIGHT0);
GXSetChanAmbColor(
    GX_COLOR0,
    ScaleColor(white, 0.25)); // ambient scale
GXSetChanCtrl(
    GX_COLOR0,
    GX_TRUE,                // enable lighting
    GX_SRC_REG,             // ambient scale
    GX_SRC_VTX,             // mnaterial color = pre-lit color(vtx)
    GX_LIGHT0,
    GX_DF_CLAMP,                // normal diffuse light
    GX_AF_SPOT);            // spot light attenuation
//
// Set the material color register
GXSetChanMatColor( GX_COLOR0, (GXColor){0xff,0x00,0x80,0xff} );
GXSetNumChans( 1 );
```

Example: Four Attenuations for Projected Lights

This example shows how to compute local-light attenuation values for four projected-texture lights. No colors are provided per-vertex. The material color comes from the channel material register and is set to pass the attenuation (multiply by 1.0). There is no contribution from the ambient color. Each channel can be used to attenuate a projected texture in the Texture Environment (Tev) unit.

```
// Assumes that 4 light objects have been initialized and
  loaded
//
GXSetChanCtrl(
  GX_COLOR0,
  GX_TRUE,
  GX_SRC_REG,
  GX_SRC_REG,
  GX_LIGHT0,
  GX_DF_CLAMP,
  GX_AF_SPOT);
GXSetChanCtrl(
  GX_ALPHA0,
  GX_TRUE,
  GX_SRC_REG,
  GX_SRC_REG,
  GX_LIGHT1,
  GX_DF_CLAMP,
  GX_AF_SPOT);
GXSetChanCtrl(
  GX_COLOR1,
  GX_TRUE,
  GX_SRC_REG,
  GX_SRC_REG,
  GX_LIGHT2, GX_DF_CLAMP,
  GX_AF_SPOT);
GXSetChanCtrl(
  GX_ALPHA1,
GX_TRUE,
  GX_SRC_REG,
  GX_SRC_REG,
  GX_LIGHT3,
  GX_DF_CLAMP,
  GX_AF_SPOT);
GXSetChanMatColor( GX_COLOR0A0,
  WhiteOpaque);
GXSetChanMatColor( GX_COLOR1A1,
  WhiteOpaque);
GXSetChanAmbColor( GX_COLOR0A0, BlackXlu);
GXSetChanAmbColor( GX_COLOR1A1, BlackXlu);
GXSetNumChans(2);
```

GXSetChanMatColor

Description

This function sets the material color register for color channel chan. The material color is used for the channel if the material source, as set by

GXSetChanCtrl, is GX_SRC_REG.

Arguments

chan=Color channel.

Example Usage:

```
void GXSetChanMatColor(
  GXChannelID chan,
  GXColor mat_color);
```

Illustrative Example

The following example application programming interface functions and associated parameters can be used to generate texture coordinates with an unclamped diffuse lighting function or in the red component of the lit color in each vertex is used to generate a texture coordinate for looking up a one-dimensional texture map, and the second texture coordinate can be generated by the green component and used to select a one-dimensional texture line from the two-dimensional texture map:

Function	Parameters	Description
GXInitLightPos	position (x, y, z)	various
GXInitLightColor	color	appropriate value
	channel ID	always GX_COLOR0A0
	channel enable	always GX_ENABLE
	ambient source	always register src
GXSetChanCtrl	material source	always register src
	light mask	always GX_LIGHT0
	diffuse function	always GX_DF_SIGN
	attenuation function	always GX_AF_NONE
GXSetChanAmbColor	color	appropriate value
GXSetChanMatColor	color	appropriate value
	destination coord	always GX_TEXCORD0
GXSetTexCoord Gen	texgen function type	always GX_TG_SRTG
	source	always GX_TG_COOR0
	matrix	always GX_IDENTITY

Other Example Compatible Implementations

Certain of the above-described system components **50** could be implemented as other than the home video game console configuration described above. For example, one could run graphics application or other software written for system **50** on a platform with a different configuration that emulates system **50** or is otherwise compatible with it. If the other platform can successfully emulate, simulate and/or provide some or all of the hardware and software resources of system **50**, then the other platform will be able to successfully execute the software.

As one example, an emulator may provide a hardware and/or software configuration (platform) that is different from the hardware and/or software configuration (platform) of system **50**. The emulator system might include software and/or hardware components that emulate or simulate some or all of hardware and/or software components of the system for which the application software was written. For example, the emulator system could comprise a general purpose digital computer such as a personal computer, which executes a software emulator program that simulates the hardware and/or firmware of system **50**.

Some general purpose digital computers (e.g., IBM or McIntosh personal computers and compatibles) are now equipped with 3D graphics cards that provide 3D graphics pipelines compliant with DirectX or other standard 3D graphics command APIs. They may also be equipped with stereophonic sound cards that provide high quality stereophonic sound based on a standard set of sound commands. Such multimedia-hardware-equipped personal computers running emulator software may have sufficient performance to approximate the graphics and sound performance of system **50**. Emulator software controls the hardware resources on the personal computer platform to simulate the processing,. 3D graphics, sound, peripheral and other capabilities of the home video game console platform for which the game programmer wrote the game software.

FIG. **21** A illustrates an example overall emulation process using a host platform **1201**, an emulator component **1303**, and a game software executable binary image provided on a storage medium **62**. Host **1201** may be a general or special purpose digital computing device such as, for example, a personal computer, a video game console, or any other platform with sufficient computing power. Emulator **1303** may be software and/or hardware that runs on host platform **1201**, and provides a real-time conversion of commands, data and other information from storage medium

62 into a form that can be processed by host **1201**. For example, emulator **1303** fetches "source" binary-image program instructions intended for execution by system **50** from storage medium **62** and converts these program instructions to a target format that can be executed or otherwise processed by host **1201**.

As one example, in the case where the software is written for execution on a platform using an IBM PowerPC or other specific processor and the host **1201** is a personal computer using a different (e.g., Intel) processor, emulator **1303** fetches one or a sequence of binary-image program instructions from storage medium **62** and converts these program instructions to one or more equivalent Intel binary-image program instructions. The emulator **1303** also fetches and/or generates graphics commands and audio commands intended for processing by the graphics and audio processor **114**, and converts these commands into a format or formats that can be processed by hardware and/or software graphics and audio processing resources available on host **1201**. As one example, emulator **1303** may convert these commands into commands that can be processed by specific graphics and/or or sound hardware of the host **1201** (e.g., using standard DirectX, OpenGL and/or sound APIs).

An emulator **1303** used to provide some or all of the features of the video game system described above may also be provided with a graphic user interface (GUI) that simplifies or automates the selection of various options and screen modes for games run using the emulator. In one example, such an emulator **1303** may further include enhanced functionality as compared with the host platform for which the software was originally intended.

FIG. **21**B illustrates an emulation host system **1201** suitable for use with emulator **1303**. System **1201** includes a processing unit **1203** and a system memory **1205**. A system bus **1207** couples various system components including system memory **1205** to processing unit **1203**. System bus **1207** may be any of several types of bus structures including a memory bus or memory controller, a peripheral bus, and a local bus using any of a variety of bus architectures. System memory **1207** includes read only memory (ROM) **1252** and random access memory (RAM) **1254**. A basic input/output system (BIOS) **1256**, containing the basic routines that help to transfer information between elements within personal computer system **1201**, such as during start-up, is stored in the ROM **1252**. System **1201** further includes various drives and associated computer-readable media. A hard disk drive **1209** reads from and writes to a (typically fixed) magnetic hard disk **1211**. An additional (possible optional) magnetic disk drive **1213** reads from and writes to a removable "floppy" or other magnetic disk **1215**. An optical disk drive **1217** reads from and, in some configurations, writes to a removable optical disk **1219** such as a CD ROM or other optical media. Hard disk drive **1209** and optical disk drive **1217** are connected to system bus **1207** by a hard disk drive interface **1221** and an optical drive interface **1225**, respectively. The drives and their associated computer-readable media provide nonvolatile storage of computer-readable instructions, data structures, program modules, game programs and other data for personal computer system **1201**. In other configurations, other types of computer-readable media that can store data that is accessible by a computer (e.g., magnetic cassettes, flash memory cards, digital video disks, Bernoulli cartridges, random access memories (RAMs), read only memories (ROMs) and the like) may also be used.

A number of program modules including emulator **1303** may be stored on the hard disk **1211**, removable magnetic

disk **1215**, optical disk **1219** and/or the ROM **1252** and/or the RAM **1254** of system memory **1205**. Such program modules may include an operating system providing graphics and sound APIs, one or more application programs, other program modules, program data and game data. A user may enter commands and information into personal computer system **1201** through input devices such as a keyboard **1227**, pointing device **1229**, microphones, joysticks, game controllers, satellite dishes, scanners, or the like. These and other input devices can be connected to processing unit **1203** through a serial port interface **1231** that is coupled to system bus **1207**, but may be connected by other interfaces, such as a parallel port, game port Fire wire bus or a universal serial bus (USB). A monitor **1233** or other type of display device is also connected to system bus **1207** via an interface, such as a video adapter **1235**.

System **1201** may also include a modem **1154** or other network interface means for establishing communications over a network **1152** such as the Internet. Modem **1154**, which may be internal or external, is connected to system bus **123** via serial port interface **1231**. A network interface **1156** may also be provided for allowing system **1201** to communicate with a remote computing device **1150** (e.g., another system **1201**) via a local area network **1158** (or such communication may be via wide area network **1152** or other communications path such as dial-up or other communications means). System **1201** will typically include other peripheral output devices, such as printers and other standard peripheral devices.

In one example, video adapter **1235** may include a 3D graphics pipeline chip set providing fast 3D graphics rendering in response to 3D graphics commands issued based on a standard 3D graphics application programmer interface such as Microsoft's DirectX 7.0 or other version. A set of stereo loudspeakers **1237** is also connected to system bus **1207** via a sound generating interface such as a conventional "sound card" providing hardware and embedded software support for generating high quality stereophonic sound based on sound commands provided by bus **1207**. These hardware capabilities allow system **1201** to provide sufficient graphics and sound speed performance to play software stored in storage medium **62**.

All documents referenced above are hereby incorporated by reference.

While the invention has been described in connection with what is presently considered to be the most practical and preferred embodiment, it is to be understood that the invention is not to be limited to the disclosed embodiment, but on the contrary, is intended to cover various modifications and equivalent arrangements included within the scope of the appended claims. For example, as will be appreciated, although a particular cartoon lighting example is disclosed herein, the invention is not to be limited to cartoon lighting but rather, encompasses a variety of photo-realistic and non-photorealistic, texture-based and non-texture-based applications and effects that may be accomplished using an achromatic lighting parameter.

We claim:

1. A method of generating graphics images comprising:

defining at least one per-vertex lighting function;

using the per-vertex lighting function to calculate at least one parameter other than color or opacity;

subsequently using said calculated at least one parameter to modify a color or opacity; and

rendering an image based at least in part on the modified color or opacity.

2. The method of claim **1** wherein the parameter comprises at least one texture coordinate.

3. The method of claim **1** wherein the lighting function calculates said at least one parameter based at least in part on distance attenuation between a vertex and a light source.

4. The method of claim **1** wherein said lighting function calculates said at least one parameter based at least in part on the angle between the light source to vertex direction and the surface normal.

5. The method of claim **1** wherein said lighting function calculates said at least one parameter based at least in part on a vertex vector position.

6. The method of claim **1** wherein said lighting function defines a function based upon surface position, surface orientation and the position of at least one light.

7. The method of claim **1** wherein said lighting function uses either diffuse or specular lighting.

8. The method of claim **1** wherein the rendering step comprises generating a texture for a surface based at least in part on said parameter.

9. The method of claim **1** wherein said rendering step comprises texture mapping using a one-dimensional texture indexed by said at least one parameter.

10. The method of claim **1** wherein the generated parameters can be either host computed or computed using the lighting function, as required.

11. The method of claim **1** wherein one generated parameter is used to select a texel within a 1D texture and a second parameter is used to select which 1D texture to use.

12. A method of generating graphics images comprising:

defining at least one per-vertex lighting function;

using the lighting function to calculate at least one parameter other than color or opacity to be used in a subsequent modification of a color or opacity; and

rendering an image based at least in part on the calculated parameter;

wherein said lighting function calculates a negative parameter for back lighting.

13. A method of cartoon lighting comprising:

using a lighting function to generate at least one color or opacity value;

converting said at least one color or opacity value to at least one texture coordinate;

using said texture coordinate in at least one texture mapping operation; and

using the results of said texture mapping operation to modify the color or opacity of at least one visible surface in a dynamically generated cartoon image.

14. The method of claim **13** wherein said texture mapping operation comprises mapping a one-dimensional texture in response to said texture coordinate.

15. The method of claim **13** wherein said texture mapping comprises mapping brush strokes to dynamic lighting computation outputs.

16. The method of claim **13** wherein said lighting function comprises a diffuse lighting function.

17. The method of claim **13** wherein said lighting function comprises a specular lighting function.

18. The method of claim **13** wherein said lighting function comprises a distance-attenuated lighting function.

19. The method of claim **13** wherein said lighting function comprises a spotlight lighting function.

20. The method of claim **13** wherein said lighting function defines a first texture coordinate for said texture mapping and a second texture coordinate for said texture mapping is derived from a source other than said lighting function.

21. A method of cartoon lighting comprising:

using a lighting function to generate at least one color or opacity value;

converting said color or opacity value to at least one texture coordinate;

using said texture coordinate in at least one texture mapping operation; and

using the results of said texture mapping operation to modify the color or opacity of at least one visible surface in a dynamically generated cartoon image;

wherein said texture coordinate can range negatively to define cartoon backlighting.

22. A graphics system comprising:

a lighting data pipeline comprising at least first and second channels, said lighting data pipeline receiving per-vertex information and lighting definitions; and calculating lit vertex parameters in response to said per-vertex and lighting definitions;

a texture unit coupled to said lighting data pipeline, said texture unit being responsive to at least one texture coordinate, said texture unit performing at least one texture mapping operation using at least one of said lighting data pipeline outputs as said at least one texture coordinate; and

a blender coupled to said lighting data pipeline and said texture unit, said blender blending chromatic and/or opacity information obtained from said lighting data pipeline with texels obtained from said texture unit to provide a rendered image.

* * * * *