COLUMBIA UNIVERSITY

Penrose World

W4840 Final Project Report

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Content

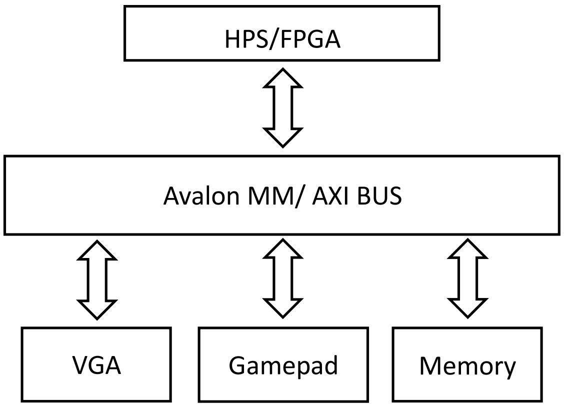
Overview

In this project, we plan to implement a 3D game, in which, a diamond can move in an incredible way by utilizing the 3D space illusion feeling. The display of 3-D image involves large amount of point-to-point projection computation which possibly have no data correlation at all. Therefore it is very convenient to implement it by high speed parallel computation. Since the nature of software-based implementation is sequential execution, it is better to do these 3-D computation using hardware instead of software. With the FPGA source on this Sockit board, we can build such parallel computation hardware architecture easily and therefore increase the processing speed of 3-D image. In this game, players can change the angle of view to create a route, which doesn't exist in 3D world. In particular, it is based on the concept of "Penrose Stair". ("Penrose Stair" is a two-dimensional depiction of a staircase in which the stairs make four 90-degree turns as they ascend or descend yet form a continuous loop, so that a person could climb them forever and never get any higher.)

This project is similar to a PSP game "Echochrome". A video of that can be found on YouTube: http://www.youtube.com/watch?v=QfICeBtVv8U

Hardware Organization

The components of our system include the HPS and FPGA core on the Sockit Board. One task for the FPGA is mainly used to build the controller (driver) of VGA and the gamepad. The FPGA is also responsible for the parallel computation of point projection on screen, generate input data stream into the VGA screen. We use gamepad to control direction of rotation, store the location information of 3-D object and its 2-D projection in the on-chip RAM and store the trigonometric value of rotation angle in the ROM. Finally, all the communications are happened on the Avlon bus. Further details about each part is shown as bellow:



FPGA

Besides the controller of all the peripherals, FPGA is also responsible for the parallel computation of each point on the object onto the screen. In each clock cycle, we generate several rays which pass through the eye and each point on the surface of target object, record the two dimensional location on the screen and calculate the distance from the screen to the object's surface. We can do the calculation of each line in parallel for the reason that every single computation has no data dependency with others. The detail of every calculation is shown in the algorithm implementation.

Gamepad

We use the gamepad to control the rotation of 3D object showing on the screen as well as the game control logic. There are four basic moving instructions in our design which controls the direction of rotation. Beyond that, several key combinations are also applied to the game logic so that we can have multiple rotation speed and can change cube location timely. The press of button will be detected by the gamepad and send to the HPS as an internal signal. Gamepad communicate with the main logic in HPS using USB port and Avlon bus. These moving instructions then define the moving operations and the angle of moving to the FPGA to generate the new rotated 3-D object. The gamepad is connected to the Sockit board using USB ports on the board. The USB is controlled by SMSC USB3300 controller.

VGA Display

The data processed by main logic in FPGA and HPS has the form of a 3-D array in which the first two columns are the X-Y coordinates of points that will display on the VGA screen. The third column indicates which surface the current shape is projected from. The VGA controller will first analyze the coordinates of input data to decide that which pixel on the screen is chosen to be light up. Then, the third column of input data will be used to decide the color of this projected surface in order to distinguish with different surfaces. Location of the cubes are given by the HPS so that we can change the location arbitrarily. The whole protocol is much like the lab3 where VGA controller response only for lighting up specific area of the screen based on the input data. More details will be given in the following chapters.

RayCasting

Image Generation

In our design we use an algorithm calling Ray-Casting to implement 3-D projection of objects onto the VGA screen. Traditional method of Ray-Casting sets a fixed point called 'eye point' at one side of the screen and the object being projecting is located at the other side of the screen. The screen is called image plane since the object will be projected onto it and form a 2-D image on the image plane. For the convenient of our discussion, the object is divided into several points. We form a ray starting from the eye point, passing through the image plane and extending further on its direction. If this ray 'hits' at one of the points on the object, i.e. one of the points on the object falls onto the ray, than this specific point of the object should be light up on the image plane. The location of this light up point would be the point on the image plane that lays on the ray. If multiple points of the object hit the ray, we simply consider the first point, i.e. the one with minimal distance to the eye point, and ignore the other options so that light up points on the image plane will always correspond to the nearest point on the object. The schematic plot is shown as below:

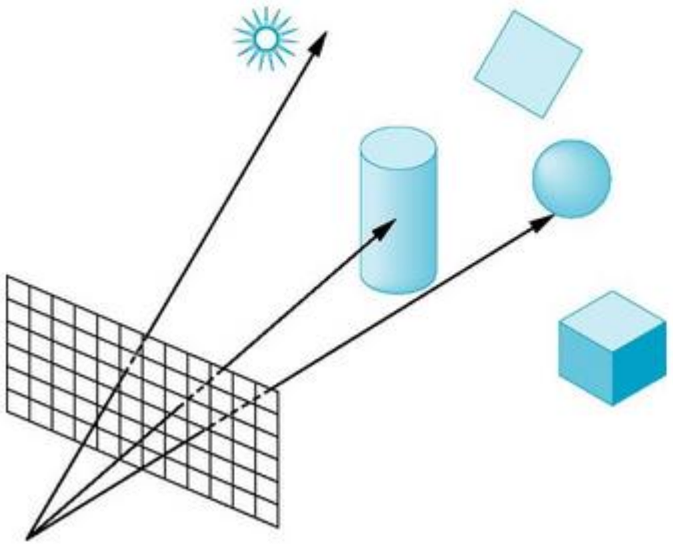


Figure 1

The main advantage of this method is that ray casting can show the shielding between multiple objects as well as distortion introduced by the difference of distance at different points on the object. This property assures that we can capture the right location relationship between multiple objects on the image plane. However, in our project, we intend to create an image of target objects on the screen that actually ignore the distortion caused by the difference in distance. Only under this particular scenario, a visual illusion will occur that forms a path between two objects that should never been formed in the real world. To achieve this, we apply a litter change to the original algorithm of the Ray-Casting. Instead of fixing a single eye pint where all the rays start at, we do a parallel projection of the objects onto the image plane. Each pixel on the image plane now have its own ray that targeting at a direction that is perpendicular to the image plane. The schematic plot of revised version of Ray-Casting is shown as below:

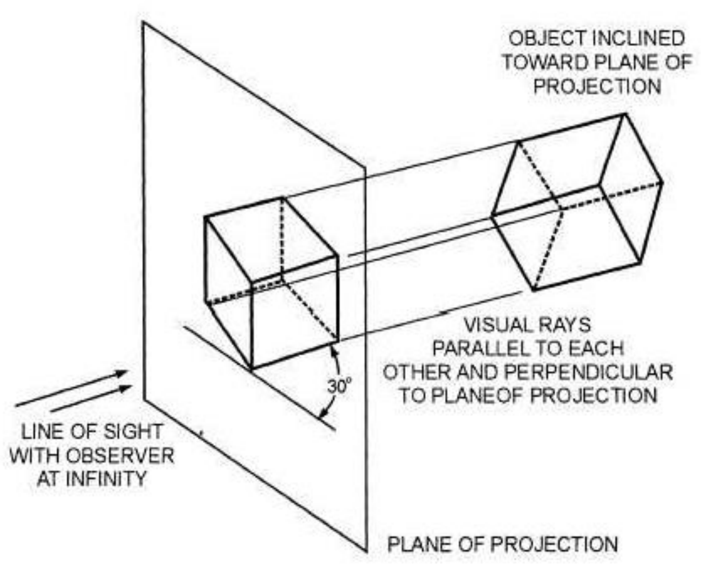

OBJECT INCLINED TOWARD PLANE OF PROJECTION
VISUAL RAYS PARALLEL TO EACH OTHER AND PERPENDICULAR TO PLANEOF PROJECTION
30°
LINE OF SIGHT WITH OBSERVER AT INFINITY
PLANE OF PROJECTION

Figure 2

Object Rotation

Every point of the target object are described using bunch of points. Each of the points has a three dimensional coordinate that stores the location information. Therefore, the rotation of object is simply a matrix multiplication that map the original coordinate to a new location using rotation matrix. The rotation matrix is illustrated as bellow:

$$RotX(\theta)=\begin{bmatrix}1 & 0 & 0\\ 0 & cos\theta & -sin\theta\\ 0 & sin\theta & cos\theta\end{bmatrix}$$

$$RotY(\gamma)=\begin{bmatrix}cos\gamma & 0 & sin\gamma\\ 0 & 1 & 0\\ -sin\gamma & 0 & cos\gamma\end{bmatrix}$$

$$RotZ(\varphi)=\begin{bmatrix}cos\varphi & -sin\varphi & 0\\ sin\varphi & cos\varphi & 0\\ 0 & 0 & 1\end{bmatrix}$$

Denote the original location of point as a three dimensional vector P and the mapped location as P':

$$P=\begin{bmatrix}x\\ y\\ z\end{bmatrix};P'=\begin{bmatrix}x'\\ y\\ z'\end{bmatrix}$$

The transformation equation is illustrated as bellow:

$$P = RotX(\theta)\, RotY(\gamma)\, RotZ(\varphi)\, P'$$

Where θ, γ, φ is the correspond angle of rotation with respect to the x-axis, y-axis and z-axis.

Flow Path of the Entire Algorithm:

1. Determine the boundary conditions of each cube. We consider only cube generations in our design. There are six surfaces in a cube. Each two of them are parallel to the other. Therefore for each cube, we should specify both the length, the width and the location of the surface. This constrain information also determining the relative location of all the objects, length and direction of each object.
2. Initialize and record the value of a three-dimension vector $R(\theta, \gamma, \varphi)$ which represents the rotation angles according to x-axis, y-axis and z-axis. After some mathematic operations describe later, we should be able to get the post-rotate location information of each object.
3. Set a reasonable step value to divide the continue boundary conditions into a boundary vector to make it more feasible to be applied with a numerical calculation. Also, set up a small noise margin of each point so that the ray wouldn't be actually hit the point to be considered as a hit. This improves the algorithm's robustness and make the image on the screen more stable.
4. Forming 256*256 pseudo pixel on the screen. Each of them consists 2*2=4 real pixels. Use these pseudo pixels as the starting point of each ray. Each clock cycle we push the rays a step further toward the object space. If any of the ray ends up at any of the object's surface, light up the corresponding pseudo pixel area on the screen to reflect a hit on the object.
5. If any of the rays hit at the surface of object, check the number of object and surface. Records the number into the buffer and color the screen based on the pre-defined mapping relationship between these numbers and different colors. If multiple hit points are detected, use a flag to indicate which one is the nearest one to the image plane.

Visual Illusion Algorithm

Function Description

Structure cp_node: stores the information such as location, projection vector matrix to every cubic.
Structure balls: store all information related to ball, such as previous and present location, direction in order to decide the location of each ball in each time slot.
Structure Plane_info: store all information related to cubic, it will show us if the cubic is connect to other cubic and the connection point.
initialize_ball(): initialize all ball structure at the beginning of game.
initialize_endPoint(): calculate the endpoint at the beginning of game, which will related to the graph we create.
initialize_plane(): initialize all plane structure at the beginning of game.
ball_moving(): control the movement of all balls in each time slot.
ball_changeplane(int ballnum): when balls jump from one cubic to the other cubic in suitable projection view, the information of ball change by this function.
calculate_jump_point(int ball_num): when the direction of balls changed, this function is used to calculated if there are jump points which equal to the paths to other cubic exist.
print_segment_info():Read and print the segment values
write_segments(const unsigned char segs[64]): Write the contents of the array to the display
int main(): the main function initialized the space at first, then listen to gamepads signal and call ball moving function.
custom_design(struct usb_keyboard_packet packet, int transferred): enable players to generate the size and location of cubic by themselves.
generate_cubic(): generate cubic with given information.
initialize(): initialize all game information when apply a new map.
calculate_pass(): when projection view changing, calculate all the connection information between every two cubic.
transfervalue(int op): change the projection view by the information passed from gamepad.

Pass Determination

We use a interesting method to implement pass determination which means determine if two cubic is connected in a given direction condition.

At first, we construct cubic by many smaller cubic with length, width and height equal to 10. For each cubic, it has two invisible small cubic in endpoint. Those invisible cubic is used to decided if we can think two cubic are connected or no. The stretch graph is shown as figure3. For each invisible cubic, it has a center node c'. For each long cubic a finite length axle wire is composed by many nodes n' with step length 1 extended in the long cubic direction. For all n', if there exist a center node c' in different cubic, the connected line between n' and c' is vertical the projection plane, the two cubic is connected by c' and n'. We can see from figure4, in view of the projection direction, two cubic are connected in our angle of view.

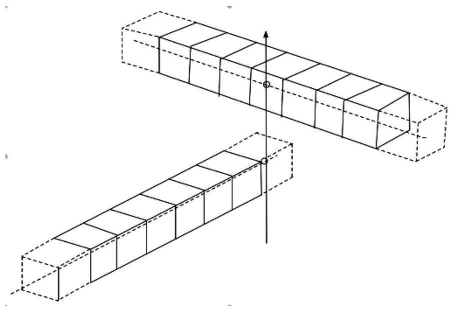


Figure 3

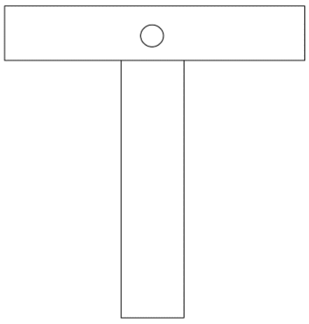


Figure 4

Three exceptions:

In the implement of the algorithm above, we find there are also some bugs. Which mean in those case, it will satisfy the algorithm condition above, however, in the view of user, the projection result is not reasonable for cubic to be connected with each other.

To make up, we will add 2 more exception to avoid those unreasonable cases.
We will list the cases and related solution method.

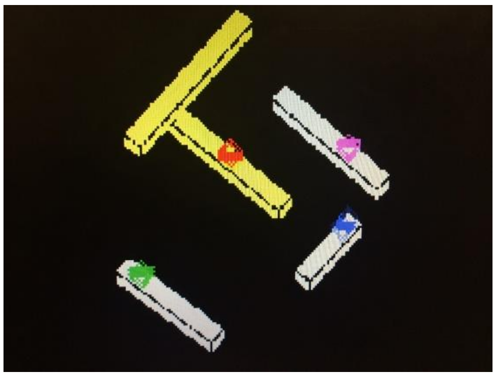


Figure 5

case1: For this case, we can add the condition that if the vector from center node c’ to n’ point out to screen. As we make our normal vector point into the screen, which means if two vector is opposite, we should not consider the two cubic are connected.

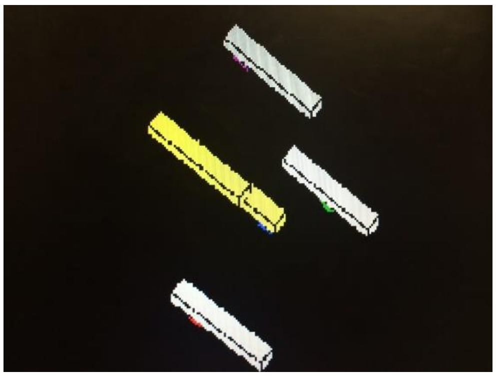


Figure 6

case2: if two cubic are parallel, we should not allow the center node c' below connected n', we implement this by the method motioned in case1 as well. Also, there is the other problem, if the marked location connected, player can't see it, we should no allow this happen. So we implement this by check if the connected vectors direction is pointed into the screen, which mean parallel to the normal vector. We should no allow this to happen.

Movement of Ball

The operation of movement of ball is complex. In this section, we will discuss the information variables which is stored in structure *balls* and their usage.

Name	Usage
plane_num	The plane number the ball is in
Bx	The x-coordinate of ball
By	The y-coordinate of ball
Bz	The z-coordinate of ball
b_dict	The moving direction of ball
next_jump_p	Whether there is jump point in front of the path
jump_x	The x-coordinate of jump point we the ball jump from
Jump_y	The y-coordinate of jump point we the ball jump from
Jump_z	The z-coordinate of jump point we the ball jump from
jump_Node	The serial number of the invisible the ball will jump to
prior_plane	the prior plane number of ball
prior_direct	the prior direction number of ball
next_is_edge	Whether the bound edge in forward path is connected to other cubic
edge_plane_num	If the bound edge in forward path is connected to other cubic, record the number of that cubic
ret_bx	If the ball is in protection state, it will record the x coordinate value for recover

ret_by	If the ball is in protection state, it will record the y coordinate value for recover
ret_bz	If the ball is in protection state, it will record the z coordinate value for recover
ret_direct	If the ball is in protection state, it will record the direction value for recover
return_protect	Record if the ball is in protection state.

The movement of ball obeys the rules below:

1. At the begin of the game, there are five cubic {c1, c2, c3, c4, c5}, the endpoint is located in c5, four balls {b1, b2, b3, b4} is placed in the start point of c1-c4. We initialize the location and ball.plane_num of balls which is based on the location of each plane. The ball.plane_num indicate which cubic the ball is in, and the change of balls location will be based on this variable, the ball will move toward the direction its located cubic extend. As we have define all start point of cubic is less than endpoint of cubic, the direction of ball are set to 1 initially which mean the balls location will increase at first.
2. Balls will keep moving in each time slot in a given direction until it reach edge or jump point.
3. Balls will calculate if there is jump points in front of them once the direction of it is set or changed or the rotation angle of projection screen change.
4. If there is no jump point in front of ball, then balls reaches the endpoint of the cubic it is in, then it change its direction to remove backward.
5. If there is a jump point in front of balls. There are two case we should discuss. (a). the ball moves from edge of a cubic to a node on axle of the other cubic. Just shown in figure7, (b). the ball moves from a node on axle of cubic to the edge of the other cubic, just shown in figure8.

In case a, when the ball moves to the edge of cubic A, it will move 5 more step, and then change its coordinate to the coordinate of center node c'. During this process, it is necessary to have a recover protection. Because when rotation angle change, as the ball is not in both two cubic, it may deorbit in this case. So if the ball is in recover protection, when rotation angle changes, we will put the ball in the jump point of this previous cubic to avoid this bug.

In case b, it is simpler. The when the ball reach the jump point, it will change its location and to the connected center node c', and change its other related information as well. We have design a method to let the ball run into the right orbit after jumping.

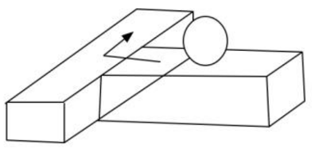


Figure 7

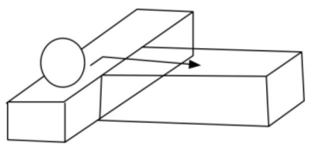


Figure 8

The flow chart for the ball moving control is shown below.

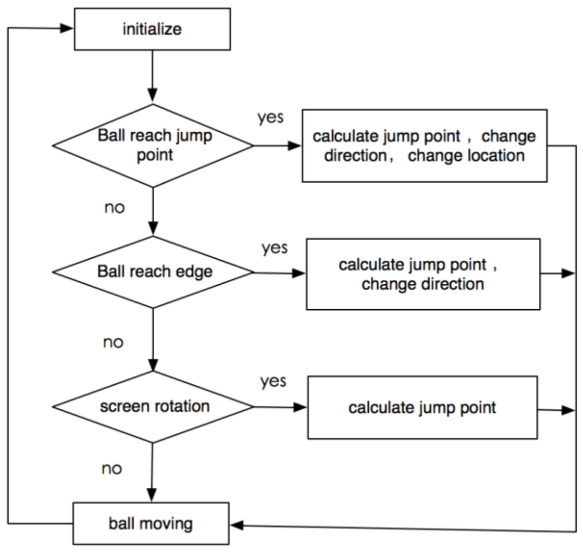


Figure 9

Hardware Implementation Details

Real time dynamic 3D graphics calculation

Hardware implementation is the core part of our project. In our implementation, we do ray casting through every pixel and dynamically configure the image which shown on the screen. To generate image on VGA screen, we have to finish two steps: rotating the object and ray casting. One major disadvantage of this method is that, before ray casting, we have to generate the rotated object and store it into a buffer. Which consume time and memory resource. To solve this problem, we used a trick method to merge these two steps into one step. We do ray casting for every pixel and rotate the casting ray in the opposite direction at the sometime. Thus, the rotation can be done at the same time as ray casting, which accelerated the calculation and avoided the necessity of storing rotated object.

Besides, to achieve real time calculation, we have to do ray casting while showing the image. We divided the screen into two parts, odd lines and even lines. For each part, we built a frame buffer. When scanning the odd line, VGA read from the odd line frame buffer to show the image on the screen and write the calculation result into the even line frame buffer. When scanning the even line, VGA read from the even line frame buffer to show the image on the screen and write the calculation result into the even line frame buffer.

Acceleration by using parallel computing

If the resolution of screen is N*N, we have to do ray casting in an N*N*N space. Since the casting ray can only move one step further per clock cycle, if we can calculate those pixels one by one, it will take N*N*N cycles to update the value in frame buffer. That will make VGA refresh rate extremely slow, as the result, objects on screen cannot move smoothly.

To solve this problem, we used parallel computing to accelerate the ray casting calculation. In our project, the VGA resolution is 256*256. Actually, we merged 4 pixels into a single one to achieve this lower resolution. I will explain late why using this lower resolution. As shown in figure 3, we group 16 pixels together. In each iteration, we calculate 16 pixels in parallel. Each iteration took 256 clock cycles. For each row of pixels, we have 16 such groups. Since we used a lower resolution, we only need to calculate a single row while scanning two lines on the screen, which contains 3200 clock cycles. It is insufficient to calculate all pixels of a single row. Thus, we separated the each row into two parts: the left part and the right part and alternatively calculates these two parts.

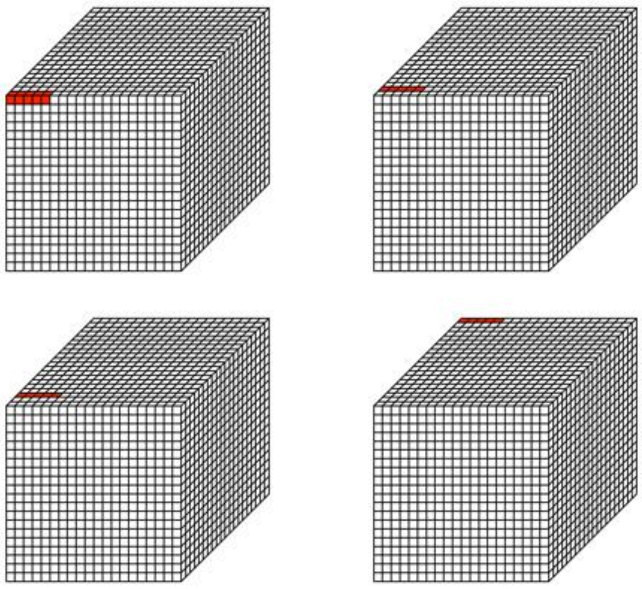


Figure 10 Ray Casting of group of pixel

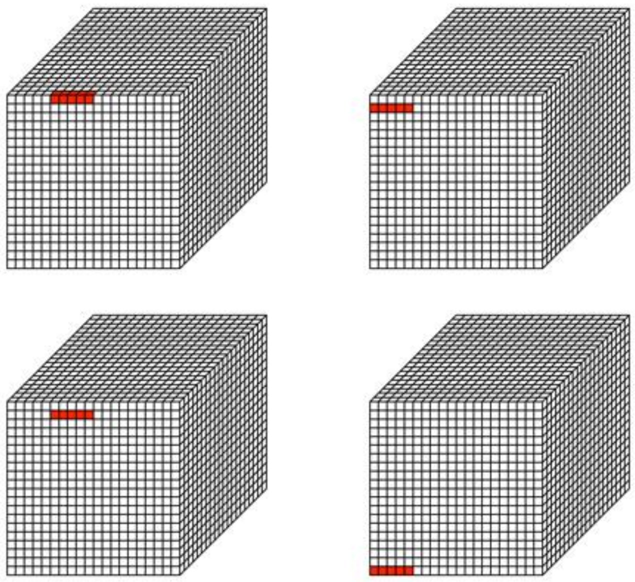


Figure 11 Iterative Calculation of Different Groups

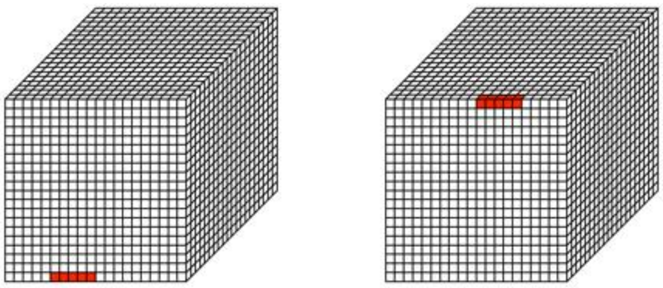


Figure 12 Alternative Calculation of Left and Right

Tradeoff between resolution and refresh rate

We chose a lower resolution because of the tradeoff between resolution and refresh rate. Refresh

rate equals to the speed we update frame buffer value. Since the pixel group size cannot be arbitrary larger (16 is the largest group size without violating timing constrain), and we cannot change the screen scan rate, lower the resolution is a good way to achieve high refresh rate.
If we change the resolution from N*N into (N/2)*(N/2), the number of pixels need to be calculated will be 1/4 of the original one. Meantime, the ray casting depth will be 1/2 of the original one because we cast in a cubic space. As a result refresh rate will be 8 times of the original one.
If we use the resolution of 640*480, it will take 269ms to refresh the image. It is too slow that, the object cannot move smoothly. When we change the resolution into 256*256. It only took 34ms to refresh the image.

Separate one moving cube into four parts

When the game start, we separate an integrated moving cube into four parts and can merge them back into an integrated one during the game (as shown in figure 4). Actually, it is a visual illusion. We created four integrated moving cubes but just show 1/4 surface of each one. Different cubes show different part of their surface. When merging them into an integrated one. The whole surface will be shown. We assigned different color to these four cubes. Thus, the integrated one looks lake a magic cube. We achieved it by alternatively highlight different parts of surface of each cube by using a MUX and changing its select single every clock cycle.

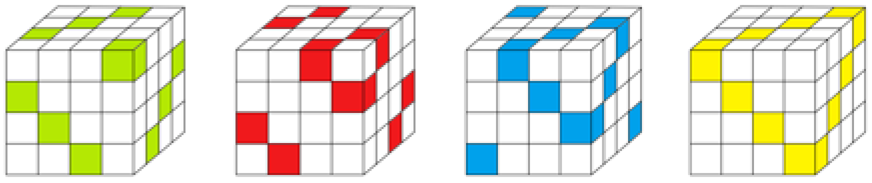


Figure 13 Four Hollow Cubes

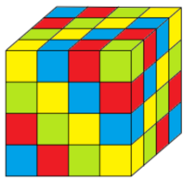


Figure 14 The Intergrated Cude

Lessons We Learnt

The first thing we learnt during this project is that how to communicate with others effectively when all the group numbers are doing their works separately. Leave comments on all the variable declarations so that others can understand what you are saying. The other thing is that divide all the works done by different people into different parts. This is particularly useful in hardware codes since the order of the code doesn’t affect its functionality at most of the time. By doing this we could understand other’s work much easier.

The other thing that we learnt is always to remember to consider how many resources we ca actually use on the Board. The complexity of our project is much higher than that of a simple function block or module. When doing the ray-casting, if we calculate all the pixels on screen at one clock cycle, it would never work because this FPGA device cannot actually handle this scale of data at one time based on the number of LUT units and DSP blocks it have. Besides, matrix multiplication involves using bunch of DSP blocks. If multiple multiplications are cascading together, the critical path delay may exceed the timing constraint settled by the board’s PLL generated clock. This may result in a lot of noise points on the screen. To archive timing closure as well as functionality robustness, we have to use and organize resources on board with careful considerations. For a VGA screen with refresh rate at 25Mhz, there is no need to calculate all the pixel point at one cycle since the user cannot see the difference if we use a lower computation frequency. Therefore, we divide the computation of the whole pixel into several parts and handle them separately. By doing this we actually reduce the usage of logic units from almost 100% to less than 50% and DSP blocks from 103% to 63% while eliminate all the noise points generated by timing violations.

The last thing we learnt from this project is to let the hardware and software do the right works. This means that we should let the hardware do the 3-D projection and shielding while let the software control the game logic and visual illusion. This allocation is based on the fact that image processing algorithms such as Ray-Casting could be done more efficient in parallel while the game logic and visual illusion has a nature of consequential. We actually implement game control in the hardware. It is much more painful and complex compare the later version implemented in software for the reason that hardware compiling is much more time consuming and hard to describe.

Experience

After one semester's learning of SoCkit Board and the usage of Quartus II design suit, we are familiarized with not only HDL languages such as SystemVerilog and Verilog, but also learnt about hardware architecture of cyclone V and HPS cores. At first we spent quite a lot of time in dealing with signed values using Verilog. Verilog is not very suitable for handling signed values such as integer. The transformation between logic and integer value should be taken extra care of because it can easily overflow during transition.

Besides, some useful tools are also introduced in lecture and project such as System Console, Qsys, SignalTap and MegaWizard. For testing of peripherals, SignalTap is always a powerful tool because it can snoop the real time signal status in FPGA. By using SignalTap we can now actually see how the signals are effected in devices such as DDR3 SDRAM which has a relative complex timing diagram and control logic. And the Qsys as well as Megawizard can provide simple and effective solutions to deal with interconnecting between IP cores and private modules.

Finally, to implement the RayCasting algorithm and visual illusion is also a very challenging work. The math behind object projection and shielding can be very abstract, which makes debug in software as well as hardware difficult.

Future Work

1. The resolution we select to display object on screen is relative low due to limit resources in our chip. In our hardware design, we use several DSP blocks to implement the multiply of the rotation matrix. Cascading of these operations increase the path delay in our circuit significantly so that we have to separate the display operation in to multi-cycles. This trade off decrease the refresh rate of VGA screen but decrease the timing violation as well. Therefore the next thing we should do would be optimize our logical path so that resources on chip can be allocated with more efficiency. Furthermore, pipeline architecture could be introduced into our design so that we can archive higher throughput and reduce critical path delay.
2. Our design didn’t use the on board DDR3 SDRAM for the reason that RAM and ROM resource are enough for image computing. But we can still use the DDR3 SDRAM for other purpose such as background music playing.
3. Due to the limitation of computing resource (LUT), we choose to decrease pixel resolution to accommodate the large parallel computing requirement of RayCasting. There are some other methods that can acquire same performance compare to RayCasting such as Z-Buffering. We can explore other solutions and get same performance as well.

Contribution

Yuanhui LUO (yl3026): Software, Game Logic design, Gamepad controller design;
Cong ZHU (cz2311): Algorithm design, Hardware design;
Yao LUO: Algorithm design, Hardware design;

Reference

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Source Code

Software

Hello.c

```
/*
  * Userspace program that communicates with the led_vga device driver
  * primarily through ioctls
  *
  * Stephen A. Edwards
  * Revised by Penrose
  *

  * Columbia University
  */

#include <stdio.h>
#include "vga_led.h"
#include <sys/ioctl.h>
#include <sys/types.h>
#include <sys/stat.h>
#include <fcntl.h>
#include <string.h>
#include <unistd.h>
#include <stdlib.h>
#include <sys/socket.h>
#include <arpa/inet.h>
#include <unistd.h>
#include "usbkeyboard.h"
#include<math.h>

#define BUFFER_size 128
#define cubnum    5

struct cpnode{
        int plane_num;
        float x_node, y_node, z_node;
        float x_va[256];
        float y_va[256];
        float z_va[256];
}cp_node[cubnum*2][cubnum];


struct Ball{
        int plane_num;              // the plane the Ball stays in
        int bx, by, bz;
        int b_dict;
        int next_jump_p;
        int jump_x, jump_y, jump_z;
        int jump_Node;
        int prior_plane;
        int prior_direct;
        int next_is_edge;
        int edge_plane_num;
        int outedge;
        int ret_bx, ret_by, ret_bz;
        int ret_direct;
        int return_protect;
}balls[cubnum-1];


struct Plane{
        int connectpoint_num;
        int N_connect[cubnum-1];
        int P_x[cubnum-1];
        int P_y[cubnum-1];
        int P_z[cubnum-1];
        int edge_node[2];
        int edge_node_connect[2];
        int edge_node_jumpx[2];
        int edge_node_jumpy[2];
        int edge_node_jumpz[2];
        int edge_node_jump_plane[2];
}Plane_info[cubnum];

float D = 0;
float D2 = 0, D3;
float precision = 0.01;
int cubic[8];
float v_x,v_y,v_z;
float v_x1,v_y1,v_z1;
float v_x2,v_y2,v_z2;
double rotate_angle_x, rotate_angle_y;
int cubic_nodes_num[cubnum];
int record_location1x, record_location2x,record_location1y, record_location2y,record_location1z,
record_location2z;
int seeSurface1, nonSeeSurface2, parallel;

  struct libusb_device_handle *keyboard;
  uint8_t endpoint_address;
  int sub0;
  int sub1;
  int sub2;
  int vga_led_fd;
  int x_angle_l;
  int y_angle_l;
  int x_angle_h;
  int y_angle_h;
  int rotation_rate = 0;
  int flag = 0;
  int ball_reach[cubnum-1];

  //end point info
    int x_ep;
    int y_ep;
    int z_ep;

  //trans cubics info
    int extend_d[cubnum];
    int x_s[cubnum];
    int x_e[cubnum];
    int y_s[cubnum];
    int y_e[cubnum];
    int z_s[cubnum];
    int z_e[cubnum];

    int extend_d1[] = {3,1,3,1,1};
    int x_s1[] = {-50, -40, 40, -20, -50};
    int x_e1[] = {-40, 20, 50, 50, 20};
    int y_s1[] = {-50, 40, 0, -20, -20};
    int y_e1[] = {-40, 50, 10, -10, -10};
    int z_s1[] = {-30, -50, -10, 40, 0};
    int z_e1[] = {50, -40, 30, 50, 10};

    int extend_d2[] = {3,3,3,3,3};
    int x_s2[] = {-50, -20, 10, 40, 40};
    int x_e2[] = {-40, -10, 20, 50, 50};
    int y_s2[] = {-50, 40, -50, 40, -50};
    int y_e2[] = {-40, 50, -40, 50, -40};
    int z_s2[] = {-10, -50, -50, -50, -10};
    int z_e2[] = {50, 10, 10, 10, 50};

    int extend_d3[] = {3,1,3,1,1};
    int x_s3[] = {-50, -40, 40, -40, -5};
    int x_e3[] = {-40, 40, 50, 40, 25};
    int y_s3[] = {30, 30, 30, 30, -5};
    int y_e3[] = {40, 40, 40, 40, 5};
    int z_s3[] = {-40, -50, -40, 40, -5};
    int z_e3[] = {40, -40, 40, 50, 5};

    int extend_d4[] = {3,1,3,1,3};
    int x_s4[] = {-50, -50, 10, -10, 40};
    int x_e4[] = {-40, 10, 20, 50, 50};
    int y_s4[] = {-50, 40, -50, 40, -50};
    int y_e4[] = {-40, 50, -40, 50, -40};
    int z_s4[] = {-10, -40, -50, 30, -10};
    int z_e4[] = {50, -30, 10, 40, 50};

    int extend_d5[] = {3,1,3,1,3};
    int x_s5[] = {-50, -30, 20, 20, 0};
    int x_e5[] = {-40, 30, 30, 80, 10};
    int y_s5[] = {-10, 40, 40, -20, -50};
    int y_e5[] = {0, 50, 50, -10, -40};
    int z_s5[] = {-50, 40, -30, 40, -10};
    int z_e5[] = {10, 50, 30, 50, 50};

    int extend_d6[] = {1,1,1,1,1};
    int x_s6[] = {-5, -5, -5, -5, -5};
    int x_e6[] = {5, 5, 5, 5, 5};
    int y_s6[] = {-5, -5, -5, -5, -5};
    int y_e6[] = {5, 5, 5, 5, 5};
    int z_s6[] = {-5, -5, -5, -5, -5};
    int z_e6[] = {5, 5, 5, 5, 5};

    int width = 5;

  static unsigned char message[VGA_LED_DIGITS] =
{ 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00,
    0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00,
    0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00,
    0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00,
    0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00,
    0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00,
    0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00,
    0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00, 0x00 };

//ball control
void initialize_ball(){
        int bii,wi;
        for(bii=0;bii<cubnum-1;bii++){
                balls[bii].plane_num = bii;
                balls[bii].bx = x_s[bii] + 5;
                balls[bii].by = y_s[bii] + 5;
                balls[bii].bz = z_s[bii] + 5;
        balls[bii].b_dict = 1;
        balls[bii].next_jump_p = 0;
        balls[bii].prior_plane = -1;
        balls[bii].prior_direct = 1;
        balls[bii].next_is_edge = 0;
        balls[bii].outedge = 0;
        }

        for(wi = 0;wi<4;wi++){
        message[40+wi*3] = balls[wi].bx;
        message[41+wi*3] = balls[wi].by-10;
        message[42+wi*3] = balls[wi].bz;
        }
        write_segments(message);
}

void initialize_endPoint(){
        x_ep = (x_s[4] + x_e[4])/2;
        y_ep = y_s[4];
        z_ep = (z_s[4] + z_e[4])/2;

        message[7] = x_ep;
        message[8] = y_ep;
        message[9] = z_ep;
}

void initialize_plane(){
        int i;
        for(i = 0;i<cubnum;i++){
                Plane_info[i].connectpoint_num = 0;
                Plane_info[i].edge_node_connect[0] = 0;
                Plane_info[i].edge_node_connect[1] = 0;
        }
}

void ball_moving(){

        int bi, wi;
        int kk, kk2;
        for (bi = 0; bi<cubnum-1; bi++) {
        if(balls[bi].bx==x_ep&&balls[bi].by==(y_ep+5)&&balls[bi].bz==z_ep) ball_reach[bi] = 1;
        if(ball_reach[bi] == 1) continue;
                if
((balls[bi].bx>=(x_s[balls[bi].plane_num]+5)&&balls[bi].bx<=(x_e[balls[bi].plane_num]-
5)&&balls[bi].by>=(y_s[balls[bi].plane_num]+5)&&
                        balls[bi].by<=(y_e[balls[bi].plane_num]-
5)&&balls[bi].bz>=(z_s[balls[bi].plane_num]+5)&&balls[bi].bz<=(z_e[balls[bi].plane_num]-
5))||balls[bi].next_is_edge == 1){
                if (balls[bi].next_jump_p == 0) {
                        switch (extend_d[balls[bi].plane_num]) {
                                case 1:{
                                        if (balls[bi].b_dict == 1) {
                                                if (balls[bi].bx < x_e[balls[bi].plane_num] - 5) {
                                                        balls[bi].bx = balls[bi].bx + balls[bi].b_dict;
                                                }
                                                else{
                                                        balls[bi].b_dict = - balls[bi].b_dict;
                                calculate_jump_point(bi);
                                                }
                                        }
                                        else if(balls[bi].b_dict == -1){
                                                if (balls[bi].bx > x_s[balls[bi].plane_num] + 5) {
                                                        balls[bi].bx = balls[bi].bx + balls[bi].b_dict;
                                                }
                                                else{
                                                        balls[bi].b_dict = - balls[bi].b_dict;
                                calculate_jump_point(bi);
                                                }
                                        }
                                        break;
                                }

                                case 2:{
                                        if (balls[bi].b_dict == 1) {
                                                if (balls[bi].by < y_e[balls[bi].plane_num] - 5) {
                                                        balls[bi].by = balls[bi].by + balls[bi].b_dict;
                }
                else{
                        balls[bi].b_dict = - balls[bi].b_dict;
        calculate_jump_point(bi);
                }
            }
            else if(balls[bi].b_dict == -1){
                if (balls[bi].by > y_s[balls[bi].plane_num] + 5) {
                        balls[bi].by = balls[bi].by + balls[bi].b_dict;
                }
                else{
                        balls[bi].b_dict = - balls[bi].b_dict;
        calculate_jump_point(bi);
                }
            }
            break;
        }

        case 3:{
            if (balls[bi].b_dict == 1) {
                if (balls[bi].bz < z_e[balls[bi].plane_num] - 5) {
                        balls[bi].bz = balls[bi].bz + balls[bi].b_dict;
                }
                else{
                        balls[bi].b_dict = - balls[bi].b_dict;
            calculate_jump_point(bi);
                }
            }
            else if(balls[bi].b_dict == -1){
                if (balls[bi].bz > z_s[balls[bi].plane_num] + 5) {
                        balls[bi].bz = balls[bi].bz + balls[bi].b_dict;
                }
                else{
                        balls[bi].b_dict = - balls[bi].b_dict;
        calculate_jump_point(bi);
                }
            }
            break;
        }

        default:
            break;
    }
```

```
}

else if(balls[bi].next_jump_p == 1&&balls[bi].next_is_edge == 0){
        switch (extend_d[balls[bi].plane_num]) {
                case 1:{
                        if (balls[bi].b_dict == 1) {
                                if (balls[bi].bx < balls[bi].jump_x) {
                                        balls[bi].bx = balls[bi].bx + balls[bi].b_dict;
                                }
                                else{
                                        ball_changeplane(bi);
                calculate_jump_point(bi);

                                }
                        }
                        else if(balls[bi].b_dict == -1){
                                if (balls[bi].bx > balls[bi].jump_x) {
                                        balls[bi].bx = balls[bi].bx + balls[bi].b_dict;
                                }
                                else{
                                        ball_changeplane(bi);
                calculate_jump_point(bi);
                                }
                        }
                        break;
                }

                case 2:{
                        if (balls[bi].b_dict == 1) {
                                if (balls[bi].by < balls[bi].jump_y) {
                                        balls[bi].by = balls[bi].by + balls[bi].b_dict;
                                }
                                else{
                                        ball_changeplane(bi);
                calculate_jump_point(bi);
                                }
                        }
                        else if(balls[bi].b_dict == -1){
                                if (balls[bi].by > balls[bi].jump_y) {
                                        balls[bi].by = balls[bi].by + balls[bi].b_dict;
                                }
                                else{
                                        ball_changeplane(bi);
                calculate_jump_point(bi);
```

```
                    }
                }
                break;
            }

            case 3:{
                if (balls[bi].b_dict == 1) {
                    if (balls[bi].bz < balls[bi].jump_z) {
                        balls[bi].bz = balls[bi].bz + balls[bi].b_dict;
                    }
                    else{
                        ball_changeplane(bi);
            calculate_jump_point(bi);
                    }
                }
                else if(balls[bi].b_dict == -1){
                    if (balls[bi].bz > balls[bi].jump_z) {
                        balls[bi].bz = balls[bi].bz + balls[bi].b_dict;
                    }
                    else{
                        ball_changeplane(bi);
            calculate_jump_point(bi);
                    }
                }
                break;
            }

            default:
                break;
        }
    }
else if(balls[bi].next_jump_p == 1&&balls[bi].next_is_edge == 1){

        balls[bi].ret_bx = balls[bi].jump_x;
        balls[bi].ret_by = balls[bi].jump_y;
        balls[bi].ret_bz = balls[bi].jump_z;
        balls[bi].ret_direct = balls[bi].plane_num;


    switch (extend_d[balls[bi].plane_num]) {

            case 1:{
                if (balls[bi].b_dict == 1) {
        if (balls[bi].bx >= x_e[balls[bi].plane_num] - 5)balls[bi].return_protect = 1;
```

```
else balls[bi].return_protect = 0;
                        if (balls[bi].bx < x_e[balls[bi].plane_num] + 5) {
                                balls[bi].bx = balls[bi].bx + balls[bi].b_dict;
                        }
                        else{
                                ball_changeplane(bi);
        calculate_jump_point(bi);
                        }
                }
                else if(balls[bi].b_dict == -1){
if (balls[bi].bx <= x_s[balls[bi].plane_num] + 5)balls[bi].return_protect = 1;
else balls[bi].return_protect = 0;
                        if (balls[bi].bx > x_s[balls[bi].plane_num] - 5) {
                                balls[bi].bx = balls[bi].bx + balls[bi].b_dict;
                        }
                        else{
                                ball_changeplane(bi);
        calculate_jump_point(bi);
                        }
                }
                break;
        }

        case 2:{
                if (balls[bi].b_dict == 1) {
if (balls[bi].by >= y_e[balls[bi].plane_num] - 5)balls[bi].return_protect = 1;
else balls[bi].return_protect = 0;
                        if (balls[bi].by < y_e[balls[bi].plane_num] + 5) {
                                balls[bi].by = balls[bi].by + balls[bi].b_dict;
                        }
                        else{
                                ball_changeplane(bi);
        calculate_jump_point(bi);
                        }
                }
                else if(balls[bi].b_dict == -1){
if (balls[bi].by <= y_s[balls[bi].plane_num] + 5)balls[bi].return_protect = 1;
else balls[bi].return_protect = 0;
                        if (balls[bi].by > y_s[balls[bi].plane_num] - 5) {
                                balls[bi].by = balls[bi].by + balls[bi].b_dict;
                        }
                        else{
                                ball_changeplane(bi);
        calculate_jump_point(bi);
```

```
                    }
                }
                break;
            }

            case 3:{
                if (balls[bi].b_dict == 1) {
        if (balls[bi].bz >= z_e[balls[bi].plane_num] - 5)balls[bi].return_protect = 1;
        else balls[bi].return_protect = 0;
                    if (balls[bi].bz < z_e[balls[bi].plane_num] + 5) {
                        balls[bi].bz = balls[bi].bz + balls[bi].b_dict;
                    }
                    else{
                        ball_changeplane(bi);
                calculate_jump_point(bi);
                    }
                }
                else if(balls[bi].b_dict == -1){
        if (balls[bi].bz <= z_s[balls[bi].plane_num] + 5)balls[bi].return_protect = 1;
        else balls[bi].return_protect = 0;
                    if (balls[bi].bz > z_s[balls[bi].plane_num] - 5) {
                        balls[bi].bz = balls[bi].bz + balls[bi].b_dict;
                    }
                    else{
                        ball_changeplane(bi);
            calculate_jump_point(bi);
                    }
                }
                break;
            }

            default:
                break;
        }
}
}


    else{
    ////printf("try");
        switch (extend_d[balls[bi].plane_num]){
            case 1: {
        if(balls[bi].b_dict==-1&&balls[bi].bx<x_s[balls[bi].plane_num]-5)balls[bi].b_dict=1;
        if(balls[bi].b_dict==1&&balls[bi].bx>x_e[balls[bi].plane_num]+5)balls[bi].b_dict=-1;
```

```
                                        balls[bi].bx += balls[bi].b_dict;
                                        break;
                                    }
                                    case 2: {
                               if(balls[bi].b_dict==-1&&balls[bi].by<y_s[balls[bi].plane_num]-5)balls[bi].b_dict=1;
                              if(balls[bi].b_dict==1&&balls[bi].by>y_e[balls[bi].plane_num]+5)balls[bi].b_dict=-1;
                                        balls[bi].by += balls[bi].b_dict;
                                        break;
                                    }
                                    case 3: {
                               if(balls[bi].b_dict==-1&&balls[bi].bz<z_s[balls[bi].plane_num]-5)balls[bi].b_dict=1;
                              if(balls[bi].b_dict==1&&balls[bi].bz>z_e[balls[bi].plane_num]+5)balls[bi].b_dict=-1;
                                        balls[bi].bz += balls[bi].b_dict;
                                        break;
                                    }
                                }
                            }

}

    for(kk=0;kk<cubnum;kk++){
        for(kk2=kk+1;kk2<cubnum;kk2++)
        if(balls[kk].return_protect==0&&balls[kk2].return_protect==0)combine_ball(kk,kk2);
    }
// write message
    for(wi = 0;wi<4;wi++){
        message[40+wi*3] = balls[wi].bx;
        message[41+wi*3] = balls[wi].by-10;
        message[42+wi*3] = balls[wi].bz;
    }
    write_segments(message);
    ////printf("x, y, z = %d, %d, %d\n", message[40], message[41], message[42]);
    ////printf("x, y, z = %d, %d, %d\n", balls[0].bx, balls[0].by, balls[0].bz);
    ////printf("dict    = %d\n", balls[0].b_dict);
    //sleep(1);
}


void ball_changeplane(int ballnum){

    if(balls[ballnum].next_is_edge == 0){
    balls[ballnum].next_jump_p = 0;
    balls[ballnum].prior_plane = balls[ballnum].plane_num;
```

```
//
        balls[ballnum].bx = (int)cp_node[balls[ballnum].jump_Node][0].x_node;
        balls[ballnum].by = (int)cp_node[balls[ballnum].jump_Node][0].y_node;
        balls[ballnum].bz = (int)cp_node[balls[ballnum].jump_Node][0].z_node;

        if(extend_d[cp_node[balls[ballnum].jump_Node][0].plane_num]                    ==
extend_d[balls[ballnum].plane_num]){

switch(extend_d[balls[ballnum].plane_num]){

                case                    1:{if(((balls[ballnum].bx                      +
balls[ballnum].prior_direct*5)!=(x_s[cp_node[balls[ballnum].jump_Node][0].plane_num]))&&((b
alls[ballnum].bx                                                                        +
balls[ballnum].prior_direct*5)!=(x_e[cp_node[balls[ballnum].jump_Node][0].plane_num])))balls[
ballnum].prior_direct = -balls[ballnum].b_dict;printf("%d\n",balls[ballnum].prior_direct);break;}
                case                    2:{if(((balls[ballnum].by                      +
balls[ballnum].prior_direct*5)!=(y_s[cp_node[balls[ballnum].jump_Node][0].plane_num]))&&((b
alls[ballnum].by                                                                        +
balls[ballnum].prior_direct*5)!=(y_e[cp_node[balls[ballnum].jump_Node][0].plane_num])))balls[
ballnum].prior_direct = -balls[ballnum].b_dict;printf("%d\n",balls[ballnum].prior_direct);break;}
                case                    3:{if(((balls[ballnum].bz                      +
balls[ballnum].prior_direct*5)!=(z_s[cp_node[balls[ballnum].jump_Node][0].plane_num]))&&((b
alls[ballnum].bz                                                                        +
balls[ballnum].prior_direct*5)!=(z_e[cp_node[balls[ballnum].jump_Node][0].plane_num])))balls[
ballnum].prior_direct = -balls[ballnum].b_dict;printf("%d\n",balls[ballnum].prior_direct);break;}
            }


        }
        else

        balls[ballnum].prior_direct = balls[ballnum].b_dict;

balls[ballnum].plane_num = cp_node[balls[ballnum].jump_Node][0].plane_num;
        if (balls[ballnum].jump_Node%2==0) {
            balls[ballnum].b_dict = 1;
        }
        else
            balls[ballnum].b_dict = -1;
        balls[ballnum].return_protect = 0;
        }
        else if(balls[ballnum].next_is_edge == 1){
```

```
        balls[ballnum].next_jump_p = 0;

                if(extend_d[balls[ballnum].edge_plane_num] == extend_d[balls[ballnum].plane_num])
        balls[ballnum].b_dict = -balls[ballnum].prior_direct;
        else{
        balls[ballnum].b_dict = balls[ballnum].prior_direct;
}
        balls[ballnum].prior_plane = balls[ballnum].plane_num;
        balls[ballnum].plane_num = balls[ballnum].edge_plane_num;
        balls[ballnum].bx = balls[ballnum].jump_x;
                balls[ballnum].by = balls[ballnum].jump_y;
        balls[ballnum].bz = balls[ballnum].jump_z;
        balls[ballnum].next_is_edge = 0;
        balls[ballnum].return_protect = 0;

        }
}



// get the nearest jump point for ball
void calculate_jump_point(int ball_num){
        int i;
        int x_value, y_value, z_value;
        int first = 1;
        int diff;
        int diff_value1;
        int diff_value2;
        int pass = 0;
        diff = extend_d[balls[ball_num].plane_num];
        balls[ball_num].next_jump_p = 0;
        balls[ball_num].next_is_edge = 0;
        if (Plane_info[balls[ball_num].plane_num].connectpoint_num != 0){
                for (i = 0; i<Plane_info[balls[ball_num].plane_num].connectpoint_num; i++){
                        //if the jumping point is in front of balls direct
                        if                                              (((Plane_info[balls[ball_num].plane_num].P_x[i]-
balls[ball_num].bx)/balls[ball_num].b_dict)>0||((Plane_info[balls[ball_num].plane_num].P_y[i]-
balls[ball_num].by)/balls[ball_num].b_dict)>0||((Plane_info[balls[ball_num].plane_num].P_z[i]-
balls[ball_num].bz)/balls[ball_num].b_dict)>0) {

                        if(balls[ball_num].bx                                                                   !=
Plane_info[balls[ball_num].plane_num].P_x[i]||balls[ball_num].by                                   !=
Plane_info[balls[ball_num].plane_num].P_y[i]||balls[ball_num].bz                                   !=
Plane_info[balls[ball_num].plane_num].P_z[i]){
```

```
                    balls[ball_num].next_jump_p = 1;
            }
                if (first==1) {
                    first = 0;
                    balls[ball_num].jump_Node                                                    =
Plane_info[balls[ball_num].plane_num].N_connect[i];
                    balls[ball_num].jump_x =Plane_info[balls[ball_num].plane_num].P_x[i];
                    balls[ball_num].jump_y =Plane_info[balls[ball_num].plane_num].P_y[i];
                    balls[ball_num].jump_z =Plane_info[balls[ball_num].plane_num].P_z[i];
                    switch (diff) {
                        case 1:{
                            diff_value1   =   Plane_info[balls[ball_num].plane_num].P_x[i]-
balls[ball_num].bx;
                            break;
                        }
                        case 2:{
                            diff_value1   =   Plane_info[balls[ball_num].plane_num].P_y[i]-
balls[ball_num].by;
                            break;
                        }
                        case 3:{
                            diff_value1=      Plane_info[balls[ball_num].plane_num].P_z[i]-
balls[ball_num].bz;
                            break;
                        }
                        default:
                            break;
                    }
                    diff_value2 = diff_value1;
                }
                else{
                    switch (diff) {
                        case 1:{
                            diff_value1   =   Plane_info[balls[ball_num].plane_num].P_x[i]-
balls[ball_num].bx;
                            break;
                        }
                        case 2:{
                            diff_value1   =   Plane_info[balls[ball_num].plane_num].P_y[i]-
balls[ball_num].by;
                            break;
                        }
                        case 3:{
                            diff_value1   =   Plane_info[balls[ball_num].plane_num].P_z[i]-
balls[ball_num].bz;
                                        break;
                                    }
                                    default:
                                        break;
                              }
                              if (diff_value1<diff_value2) {
                                    balls[ball_num].jump_Node                                    =
Plane_info[balls[ball_num].plane_num].N_connect[i];
                                    balls[ball_num].jump_x
=Plane_info[balls[ball_num].plane_num].P_x[i];
                                    balls[ball_num].jump_y
=Plane_info[balls[ball_num].plane_num].P_y[i];
                                    balls[ball_num].jump_z
=Plane_info[balls[ball_num].plane_num].P_z[i];
                              }
                        }
                  }
            }
      }
      if(balls[ball_num].next_jump_p == 0){

      if(Plane_info[balls[ball_num].plane_num].edge_node_connect[0]==1&&balls[ball_num].b_d
ict==-1){
                  balls[ball_num].next_is_edge = 1;
                  balls[ball_num].jump_x                                             =
Plane_info[balls[ball_num].plane_num].edge_node_jumpx[0];
                  balls[ball_num].jump_y                                             =
Plane_info[balls[ball_num].plane_num].edge_node_jumpy[0];
                  balls[ball_num].jump_z                                             =
Plane_info[balls[ball_num].plane_num].edge_node_jumpz[0];
                  balls[ball_num].edge_plane_num                                     =
Plane_info[balls[ball_num].plane_num].edge_node_jump_plane[0];
                  balls[ball_num].next_jump_p = 1;
            }
            else
if(Plane_info[balls[ball_num].plane_num].edge_node_connect[1]==1&&balls[ball_num].b_dict==
1){
                  balls[ball_num].next_is_edge = 1;
                  balls[ball_num].jump_x                                             =
Plane_info[balls[ball_num].plane_num].edge_node_jumpx[1];
                  balls[ball_num].jump_y                                             =
Plane_info[balls[ball_num].plane_num].edge_node_jumpy[1];
                  balls[ball_num].jump_z                                             =
Plane_info[balls[ball_num].plane_num].edge_node_jumpz[1];
                        balls[ball_num].edge_plane_num                                                  =
Plane_info[balls[ball_num].plane_num].edge_node_jump_plane[1];
                        balls[ball_num].next_jump_p = 1;
                }
        }
}

/* Read and print the segment values */
void print_segment_info() {
    vga_led_arg_t vla;
    int i;

    for (i = 0 ; i < VGA_LED_DIGITS ; i++) {
        vla.digit = i;
        if (ioctl(vga_led_fd, VGA_LED_READ_DIGIT, &vla)) {
            perror("ioctl(VGA_LED_READ_DIGIT) failed");
            return;
        }
    }
}

/* Write the contents of the array to the display */
void write_segments(const unsigned char segs[64])
{
    vga_led_arg_t vla;
    int i;
    for (i = 0 ; i < VGA_LED_DIGITS ; i++) {
        vla.digit = i;
        vla.segments = segs[i];
        if (ioctl(vga_led_fd, VGA_LED_WRITE_DIGIT, &vla)) {
            perror("ioctl(VGA_LED_WRITE_DIGIT) failed");
            return;
        }
    }
}

int main()
{

/*    Variable defination    */
    int i;
    static const char filename[] = "/dev/vga_led";
    int operation;
    int err, col;
    struct usb_keyboard_packet packet;
    int transferred;
    char keystate[12];

    x_angle_l = 0;
    y_angle_l = 0;
    x_angle_h = 0;
    y_angle_h = 0;

    memcpy(&extend_d, &extend_d1, 20);
    memcpy(&x_s, &x_s1, 20);
    memcpy(&x_e, &x_e1, 20);
    memcpy(&y_s, &y_s1, 20);
    memcpy(&y_e, &y_e1, 20);
    memcpy(&z_s, &z_s1, 20);
    memcpy(&z_e, &z_e1, 20);

    vga_led_arg_t vla;

  /*    Open the keyboard    */
    if ( (keyboard = openkeyboard(&endpoint_address)) == NULL ) {
        fprintf(stderr, "Did not find a keyboard\n");
        exit(1);
    }
    //printf("VGA LED Userspace program started\n");
    if ( (vga_led_fd = open(filename, O_RDWR)) == -1) {
        fprintf(stderr, "could not open %s\n", filename);
        return -1;
    }
    //printf("initial state: ");
    print_segment_info();
    write_segments(message);
    //printf("current state: ");
    print_segment_info();
    //printf("VGA LED Userspace program started\n");
    if ( (vga_led_fd = open(filename, O_RDWR)) == -1) {
        fprintf(stderr, "could not open %s\n", filename);
        return -1;
    }
    //printf("initial state: ");
    print_segment_info();
    write_segments(message);
    //printf("current state: ");
    print_segment_info();



change_level:
printf("initialize\n");
    initialize();
    operation = 3;rotation_rate = 2;for(i=0;i<25600000;i++){if(i%100000 == 0)transfervalue
        (operation);}flag = 1;
    operation = 1;rotation_rate = 2;for(i=0;i<25600000;i++){if(i%100000 == 0)transfervalue
(operation);}flag = 1;
    transfervalue(5);
/* Look for and handle keypresses */
    for (;;) {

        if(ball_reach[3] == 1&&ball_reach[2] == 1&&ball_reach[1] == 1&&ball_reach[0] == 1)
message[6] = 0x01;
        ball_moving();
        operation = 0;
        libusb_interrupt_transfer(keyboard, endpoint_address,
                            (unsigned char *) &packet, sizeof(packet),
                            &transferred, 0);
        if (transferred == sizeof(packet)) {
                if(packet.keycode[3] == 0x06&&packet.keycode[4] == 0x00){operation = 1;rotation_rate
= 1;}
                else if(packet.keycode[3] == 0x02&&packet.keycode[4] == 0x00){operation =
2;rotation_rate = 1;}
                else if(packet.keycode[3] == 0x00&&packet.keycode[4] == 0x00){operation =
3;rotation_rate = 1;}
                else if(packet.keycode[3] == 0x04&&packet.keycode[4] == 0x00){operation =
4;rotation_rate = 1;}
                else if(packet.keycode[3] == 0x16&&packet.keycode[4] == 0x00){operation =
1;rotation_rate = 4;}
                else if(packet.keycode[3] == 0x12&&packet.keycode[4] == 0x00){operation =
2;rotation_rate = 4;}
                else if(packet.keycode[3] == 0x10&&packet.keycode[4] == 0x00){operation =
3;rotation_rate = 4;}
                else if(packet.keycode[3] == 0x14&&packet.keycode[4] == 0x00){operation =
4;rotation_rate = 4;}
                else if(packet.keycode[3] == 0x4f&&packet.keycode[4] == 0x00){operation = 5;}
                else if(packet.keycode[4] == 0x04&&packet.keycode[3] == 0x0f&&flag == 0)
                        {operation = 1;rotation_rate = 2;for(i=0;i<5120000;i++){if(i%10000 ==
0)transfervalue         (operation);}flag = 1;}
                else if(packet.keycode[4] == 0x08&&packet.keycode[3] == 0x0f&&flag == 0)
```

```
                    {operation = 2;rotation_rate = 2;for(i=0;i<5120000;i++){if(i%10000 ==
0)transfervalue(operation);}flag = 1;}
            else if(packet.keycode[3] == 0x1f&&packet.keycode[4] == 0x0c){operation = 6;}
            else if(packet.keycode[3] == 0x2f&&packet.keycode[4] == 0x0c){operation = 7;}
            else if(packet.keycode[3] == 0x4f&&packet.keycode[4] == 0x0c){operation = 8;}
            else if(packet.keycode[3] == 0x8f&&packet.keycode[4] == 0x0c){operation = 9;}
            else if(packet.keycode[3] == 0x0f&&packet.keycode[4] == 0x0d){operation = 10;}
            else if(packet.keycode[3] == 0x0f&&packet.keycode[4] == 0x0e){operation = 11;}

            if(packet.keycode[3] == 0x0f&&packet.keycode[4] == 0x00)flag=0;

      }

      if(operation == 6||operation == 7||operation == 8||operation == 9||operation
==10||operation ==11){
      switch(operation)
      {
            case 6:
                  {
                        memcpy(&extend_d, &extend_d1, 20);
                        memcpy(&x_s, &x_s1, 20);
                        memcpy(&x_e, &x_e1, 20);
                        memcpy(&y_s, &y_s1, 20);
                        memcpy(&y_e, &y_e1, 20);
                        memcpy(&z_s, &z_s1, 20);
                        memcpy(&z_e, &z_e1, 20);
                        break;
                  }
            case 7:
                  {
                        memcpy(&extend_d, &extend_d2, 20);
                        memcpy(&x_s, &x_s2, 20);
                        memcpy(&x_e, &x_e2, 20);
                        memcpy(&y_s, &y_s2, 20);
                        memcpy(&y_e, &y_e2, 20);
                        memcpy(&z_s, &z_s2, 20);
                        memcpy(&z_e, &z_e2, 20);
                        break;
                  }
            case 8:
                  {
                        memcpy(&extend_d, &extend_d3, 20);
                        memcpy(&x_s, &x_s3, 20);
                        memcpy(&x_e, &x_e3, 20);
                        memcpy(&y_s, &y_s3, 20);
                        memcpy(&y_e, &y_e3, 20);
                        memcpy(&z_s, &z_s3, 20);
                        memcpy(&z_e, &z_e3, 20);
                        break;
                  }
            case 9:
                  {
                        memcpy(&extend_d, &extend_d4, 20);
                        memcpy(&x_s, &x_s4, 20);
                        memcpy(&x_e, &x_e4, 20);
                        memcpy(&y_s, &y_s4, 20);
                        memcpy(&y_e, &y_e4, 20);
                        memcpy(&z_s, &z_s4, 20);
                        memcpy(&z_e, &z_e4, 20);
                        break;
                  }
            case 10:
                  {
                        memcpy(&extend_d, &extend_d5, 20);
                        memcpy(&x_s, &x_s5, 20);
                        memcpy(&x_e, &x_e5, 20);
                        memcpy(&y_s, &y_s5, 20);
                        memcpy(&y_e, &y_e5, 20);
                        memcpy(&z_s, &z_s5, 20);
                        memcpy(&z_e, &z_e5, 20);
                        break;
                  }
            case 11:
                  {

                        memcpy(&extend_d, &extend_d6, 20);
                        memcpy(&x_s, &x_s6, 20);
                        memcpy(&x_e, &x_e6, 20);
                        memcpy(&y_s, &y_s6, 20);
                        memcpy(&y_e, &y_e6, 20);
                        memcpy(&z_s, &z_s6, 20);
                        memcpy(&z_e, &z_e6, 20);
                        initialize();
                        operation   =   3;rotation_rate   =   2;for(i=0;i<25600000;i++){if(i%100000   ==
0)transfervalue     (operation);}flag = 1;
                        operation   =   1;rotation_rate   =   2;for(i=0;i<25600000;i++){if(i%100000   ==
0)transfervalue   (operation);}flag = 1;
                        custom_design(packet,transferred);
```

```
                        break;
                    }
                break;
            }
            goto change_level;
        }

            if(operation == 1||operation == 2||operation == 3||operation == 4||operation ==5){
            transfervalue(operation);
            calculate_pass();
            message[5] =    (2*(2*(2*(2*(0 + cubic[4]) + cubic[3]) + cubic[2]) + cubic[1]) + cubic[0]);
            write_segments(message);
            }
        }
        return 0;
}

void custom_design(struct usb_keyboard_packet packet, int transferred){
        int x, y, z;
        int flag = 0;
        int length;
        int orientation;
        int i;
        for(i = 0; i<5; i++){
                x=0;
                y=0;
                z=0;
                length = 5;
                orientation = 0;
                wait:
                        libusb_interrupt_transfer(keyboard, endpoint_address,
                          (unsigned char *) &packet, sizeof(packet),
                          &transferred, 0);
                    if(!(packet.keycode[3] == 0x0f&&packet.keycode[4] == 0x00)) goto wait;

                while(packet.keycode[3] != 0x0f||packet.keycode[4] != 0x02){

                    generate_cubic();

                    if(packet.keycode[3] == 0x0f&&packet.keycode[4] == 0x00)flag=0;

                    else    if(packet.keycode[4]    ==    0x04&&packet.keycode[3]    ==    0x0f&&flag    ==
0){orientation = 0;}
                    else    if(packet.keycode[4]    ==    0x08&&packet.keycode[3]    ==    0x0f&&flag    ==
0){orientation = 1;}

                    else if(packet.keycode[3] == 0x1f&&packet.keycode[4] == 0x00&&flag == 0){
                            if(length != 125) length = length + 5;
                            flag = 1;
                    }
                    else if(packet.keycode[3] == 0x4f&&packet.keycode[4] == 0x00&&flag == 0){
                            if(length != 5) length = length - 5;
                            flag = 1;
                    }

                    else if(packet.keycode[3] == 0x00&&packet.keycode[4] == 0x00&&flag == 0){
                            if(y != -100) y = y - 10;
                            flag = 1;
                    }
                    else if(packet.keycode[3] == 0x04&&packet.keycode[4] == 0x00&&flag == 0){
                            if(y != 100) y = y + 10;
                            flag = 1;
                    }
                    else if(packet.keycode[3] == 0x06&&packet.keycode[4] == 0x00&&flag == 0){
                                    if(orientation == 0&&x != -100) x = x - 10;
                                    else if(orientation == 1&&z != -100) z = z - 10;
                            flag = 1;
                    }
                    else if(packet.keycode[3] == 0x02&&packet.keycode[4] == 0x00&&flag == 0){
                                    if(orientation == 0&&x != 100) x = x + 10;
                                    else if(orientation == 1&&z != 100) z = z + 10;
                            flag = 1;
                    }


                    if(orientation == 0){
                            extend_d[i] = 3;
                            x_s[i] = x - width;
                            x_e[i] = x + width;
                            y_s[i] = y - width;
                            y_e[i] = y + width;
                            z_s[i] = z - length;
                            z_e[i] = z + length;
                    } else{
                            extend_d[i] = 1;
                            x_s[i] = x - length;
                            x_e[i] = x + length;
                            y_s[i] = y - width;
```

```
                        y_e[i] = y + width;
                        z_s[i] = z - width;
                        z_e[i] = z + width;
                    }

                    initialize_endPoint();
                    initialize_ball();

                        libusb_interrupt_transfer(keyboard, endpoint_address,
                          (unsigned char *) &packet, sizeof(packet),
                          &transferred, 0);
                }
        }
}

void generate_cubic()
{
        int i,j,k;
        k = 10;
        for(i = 0; i<cubnum; i++){

                message[k] = x_s[i];
                k++;
                message[k] = x_e[i];
                k++;
                message[k] = y_s[i];
                k++;
                message[k] = y_e[i];
                k++;
                message[k] = z_s[i];
                k++;
                message[k] = z_e[i];
                k++;
        }
        write_segments(message);
}


void initialize(){

        ball_reach[0] = 0;
        ball_reach[1] = 0;
        ball_reach[2] = 0;
        ball_reach[3] = 0;
        message[0] = 0x00;
        message[1] = 0x00;
        message[2] = 0x00;
        message[3] = 0x00;
        message[5] = 0x00;
        message[6] = 0x00;
        x_angle_l = 0;
        y_angle_l = 0;
        x_angle_h = 0;
        y_angle_h = 0;

        generate_cubic();

        int i,j,k;

        for(i = 0;i<cubnum;i++){
                Plane_info[i].edge_node[0] = 2*i;
                Plane_info[i].edge_node[1] = 2*i + 1;
        }

        initialize_ball();
        initialize_endPoint();
        for (i = 0; i<cubnum; i++) {
                switch (extend_d[i]) {
                        case 1:
                                cubic_nodes_num[i] = ((x_e[i] - x_s[i])/10 - 2)*10 + 10;
                                break;
                        case 2:
                                cubic_nodes_num[i] = ((y_e[i] - y_s[i])/10 - 2)*10 + 10;
                                break;
                        case 3:
                                cubic_nodes_num[i] = ((z_e[i]- z_s[i])/10 - 2)*10 + 10;
                                break;
                        default:
                                break;
                }

        }

//generate all comparing nodes, stored in structuren cp_node[cubnum*2][cubnum]
        for (i = 0; i<2*cubnum; i++) {
                for (j = 0; j<cubnum; j++) {
                        cp_node[i][j].plane_num = i/2;
```

```
            switch (extend_d[i/2]) {
                case 1:{
                    if (i % 2 ==0)
                        cp_node[i][j].x_node = x_s[i/2] - width;
                    else
                        cp_node[i][j].x_node = x_e[i/2] + width;
                    cp_node[i][j].y_node = y_s[i/2] + width;
                    cp_node[i][j].z_node = z_s[i/2] + width;
                    break;
                }
                case 2:{
                    if (i % 2 ==0)
                        cp_node[i][j].y_node = y_s[i/2] - width;
                    else
                        cp_node[i][j].y_node = y_e[i/2] + width;
                    cp_node[i][j].x_node = x_s[i/2] + width;
                    cp_node[i][j].z_node = z_s[i/2] + width;
                    break;
                }
                case 3:{
                    if (i % 2 ==0)
                        cp_node[i][j].z_node = z_s[i/2] - width;
                    else
                        cp_node[i][j].z_node = z_e[i/2] + width;
                    cp_node[i][j].y_node = y_s[i/2] + width;
                    cp_node[i][j].x_node = x_s[i/2] + width;
                    break;
                }
                default:
                    break;


            }

            if (cp_node[i][j].plane_num != j)
            for (k = 0; k<=cubic_nodes_num[j]; k++) {
                switch (extend_d[j]) {
                    case 1:{
                        cp_node[i][j].x_va[k] = x_s[j] + 5 + k - cp_node[i][j].x_node;
                        cp_node[i][j].y_va[k] = y_s[j] + 5 - cp_node[i][j].y_node;
                        cp_node[i][j].z_va[k] = z_s[j] + 5 - cp_node[i][j].z_node;
                        D     =     cp_node[i][j].x_va[k]*cp_node[i][j].x_va[k]     +
cp_node[i][j].y_va[k] *cp_node[i][j].y_va[k]
                        + cp_node[i][j].z_va[k]*cp_node[i][j].z_va[k];
                        D = sqrt(D);
                        cp_node[i][j].x_va[k] = cp_node[i][j].x_va[k]/D;
                        cp_node[i][j].y_va[k] = cp_node[i][j].y_va[k]/D;
                        cp_node[i][j].z_va[k] = cp_node[i][j].z_va[k]/D;
                        break;
                    }
                    case 2:{
                        cp_node[i][j].x_va[k] = x_s[j] + 5     - cp_node[i][j].x_node;
                        cp_node[i][j].y_va[k] = y_s[j] + 5 + k - cp_node[i][j].y_node;
                        cp_node[i][j].z_va[k] = z_s[j] + 5 - cp_node[i][j].z_node;
                        D          =          cp_node[i][j].x_va[k]*cp_node[i][j].x_va[k]          +
cp_node[i][j].y_va[k] *cp_node[i][j].y_va[k]
                        + cp_node[i][j].z_va[k]*cp_node[i][j].z_va[k];
                        D = sqrt(D);
                        cp_node[i][j].x_va[k] = cp_node[i][j].x_va[k]/D;
                        cp_node[i][j].y_va[k] = cp_node[i][j].y_va[k]/D;
                        cp_node[i][j].z_va[k] = cp_node[i][j].z_va[k]/D;
                        break;
                    }
                    case 3:{
                        cp_node[i][j].x_va[k] = x_s[j] + 5 - cp_node[i][j].x_node;
                        cp_node[i][j].y_va[k] = y_s[j] + 5 - cp_node[i][j].y_node;
                        cp_node[i][j].z_va[k] = z_s[j] + 5 + k - cp_node[i][j].z_node;
                        D          =          cp_node[i][j].x_va[k]*cp_node[i][j].x_va[k]          +
cp_node[i][j].y_va[k] *cp_node[i][j].y_va[k]
                        + cp_node[i][j].z_va[k]*cp_node[i][j].z_va[k];
                        D = sqrt(D);
                        cp_node[i][j].x_va[k] = cp_node[i][j].x_va[k]/D;
                        cp_node[i][j].y_va[k] = cp_node[i][j].y_va[k]/D;
                        cp_node[i][j].z_va[k] = cp_node[i][j].z_va[k]/D;
                        break;
                    }

                    default:
                        break;
                }
            }
        }
    }
}



void calculate_pass(){
	int ci, cj, ck;
	int bi;
	rotate_angle_x = 2*3.14159*(x_angle_l + x_angle_h*256)/4096;
	rotate_angle_y = 2*3.14159*(y_angle_l + y_angle_h*256)/4096;

	initialize_plane();
	v_x = 0.0;
	v_y = 0.0;
	v_z = 1.0;



	v_x1 = v_x;
	v_y1 = cos(rotate_angle_y)*v_y + sin(rotate_angle_y)*v_z;
	v_z1 = -sin(rotate_angle_y)*v_y + cos(rotate_angle_y)*v_z;

	v_x2 = -sin(rotate_angle_x)*v_z1 + cos(rotate_angle_x)*v_x1;
	v_y2 = v_y1;
	v_z2 = cos(rotate_angle_x)*v_z1 + sin(rotate_angle_x)*v_x1;


	for (cj = 0; cj<cubnum; cj++) {
		cubic[cj] = 0;
	}
	for(ci=0;ci<2*cubnum;ci++)
		for (cj=0; cj<cubnum; cj++) {
			if ((cubic[cj]!=1)||(cubic[cp_node[ci][cj].plane_num] != 1))
			for (ck = 0; ck<=cubic_nodes_num[cj]; ck++) {
				if (cubic[cj]==1&&cubic[cp_node[ci][cj].plane_num] == 1)break;
				if (cp_node[ci][cj].plane_num!=(cj)) {

D2 = sqrt((v_x2-cp_node[ci][cj].x_va[ck])*(v_x2-cp_node[ci][cj].x_va[ck]) + (v_y2-cp_node[ci][cj].y_va[ck])*(v_y2-cp_node[ci][cj].y_va[ck]) + (v_z2-cp_node[ci][cj].z_va[ck])*(v_z2-cp_node[ci][cj].z_va[ck]))<sqrt((v_x2+cp_node[ci][cj].x_va[ck])*(v_x2+cp_node[ci][cj].x_va[ck]) + (v_y2+cp_node[ci][cj].y_va[ck])*(v_y2+cp_node[ci][cj].y_va[ck]) + (v_z2+cp_node[ci][cj].z_va[ck])*(v_z2+cp_node[ci][cj].z_va[ck]))?sqrt((v_x2-cp_node[ci][cj].x_va[ck])*(v_x2-cp_node[ci][cj].x_va[ck]) + (v_y2-cp_node[ci][cj].y_va[ck])*(v_y2-cp_node[ci][cj].y_va[ck]) + (v_z2-cp_node[ci][cj].z_va[ck])*(v_z2-cp_node[ci][cj].z_va[ck])):sqrt((v_x2+cp_node[ci][cj].x_va[ck])*(v_x2+cp_node[ci][cj].x_va[ck]) + (v_y2+cp_node[ci][cj].y_va[ck])*(v_y2+cp_node[ci][cj].y_va[ck]) + (v_z2+cp_node[ci][cj].z_va[ck])*(v_z2+cp_node[ci][cj].z_va[ck]));

		switch(extend_d[ci/2]){
			case 1:{
```

```
                D3 = (v_x2-1)*(v_x2-1) + (v_y2-0)*(v_y2-0) + (v_z2-0)*(v_z2-0);
                break;
            }
            case 2:{
                D3 = (v_x2-0)*(v_x2-0) + (v_y2-1)*(v_y2-1) + (v_z2-0)*(v_z2-0);
                break;
            }
            case 3:{
                D3 = (v_x2-0)*(v_x2-0) + (v_y2-0)*(v_y2-0) + (v_z2-1)*(v_z2-1);
                break;
            }
        }

            seeSurface1 = (ci%2 ? D3 > 2 : D3 < 2) && (sqrt((v_x2-
cp_node[ci][cj].x_va[ck])*(v_x2-cp_node[ci][cj].x_va[ck]) + (v_y2-cp_node[ci][cj].y_va[ck])*(v_y2-
cp_node[ci][cj].y_va[ck]) + (v_z2-cp_node[ci][cj].z_va[ck])*(v_z2-
cp_node[ci][cj].z_va[ck]))<sqrt((v_x2+cp_node[ci][cj].x_va[ck])*(v_x2+cp_node[ci][cj].x_va[ck]) +
(v_y2+cp_node[ci][cj].y_va[ck])*(v_y2+cp_node[ci][cj].y_va[ck]) +
(v_z2+cp_node[ci][cj].z_va[ck])*(v_z2+cp_node[ci][cj].z_va[ck])));
            nonSeeSurface2 = !(ci%2 ? D3 > 2 : D3 < 2) && (sqrt((v_x2-
cp_node[ci][cj].x_va[ck])*(v_x2-cp_node[ci][cj].x_va[ck]) + (v_y2-cp_node[ci][cj].y_va[ck])*(v_y2-
cp_node[ci][cj].y_va[ck]) + (v_z2-cp_node[ci][cj].z_va[ck])*(v_z2-
cp_node[ci][cj].z_va[ck]))>sqrt((v_x2+cp_node[ci][cj].x_va[ck])*(v_x2+cp_node[ci][cj].x_va[ck]) +
(v_y2+cp_node[ci][cj].y_va[ck])*(v_y2+cp_node[ci][cj].y_va[ck]) +
(v_z2+cp_node[ci][cj].z_va[ck])*(v_z2+cp_node[ci][cj].z_va[ck])));
            parallel = (extend_d[ci/2] == extend_d[cj]) && (sqrt((v_x2-
cp_node[ci][cj].x_va[ck])*(v_x2-cp_node[ci][cj].x_va[ck]) + (v_y2-cp_node[ci][cj].y_va[ck])*(v_y2-
cp_node[ci][cj].y_va[ck]) + (v_z2-cp_node[ci][cj].z_va[ck])*(v_z2-
cp_node[ci][cj].z_va[ck]))>sqrt((v_x2+cp_node[ci][cj].x_va[ck])*(v_x2+cp_node[ci][cj].x_va[ck]) +
(v_y2+cp_node[ci][cj].y_va[ck])*(v_y2+cp_node[ci][cj].y_va[ck]) +
(v_z2+cp_node[ci][cj].z_va[ck])*(v_z2+cp_node[ci][cj].z_va[ck])));

                    if (D2<precision && !seeSurface1 && !nonSeeSurface2 && !parallel) {

                        cubic[cp_node[ci][cj].plane_num] = 1;
                        cubic[cj] = 1;
            record_location1x = (int)cp_node[ci][cj].x_node;
            record_location1y = (int)cp_node[ci][cj].y_node;
            record_location1z = (int)cp_node[ci][cj].z_node;

            switch(extend_d[cj]){
                case 1:{
                    record_location2x = (int)x_s[cj] + 5 +ck;
                    record_location2y = (int)y_s[cj] + 5;
```

```
                                        record_location2z = (int)z_s[cj] + 5;
                                        break;
                                }
                                case 2:{
                                        record_location2x = (int)x_s[cj] + 5;
                                        record_location2y = (int)y_s[cj] + 5 +ck;
                                        record_location2z = (int)z_s[cj] + 5;
                                        break;
                                }
                                case 3:{
                                        record_location2x = (int)x_s[cj] + 5;
                                        record_location2y = (int)y_s[cj] + 5;
                                        record_location2z = (int)z_s[cj] + 5 +ck;
                                        break;
                                }
                        }

                        Plane_info[ci/2].edge_node_connect[ci%2] = 1;
                        Plane_info[ci/2].edge_node_jumpx[ci%2] = record_location2x;
                        Plane_info[ci/2].edge_node_jumpy[ci%2] = record_location2y;
                        Plane_info[ci/2].edge_node_jumpz[ci%2] = record_location2z;
                        Plane_info[ci/2].edge_node_jump_plane[ci%2] = cj;



                        Plane_info[cj].N_connect[Plane_info[cj].connectpoint_num] = ci;
                        Plane_info[cj].P_x[Plane_info[cj].connectpoint_num] = record_location2x;
                        Plane_info[cj].P_y[Plane_info[cj].connectpoint_num] = record_location2y;
                        Plane_info[cj].P_z[Plane_info[cj].connectpoint_num] = record_location2z;
                        Plane_info[cj].connectpoint_num++;
                                        }
                                }
                        }
                }

        for(bi = 0; bi<cubnum-1;bi++)calculate_jump_point(bi);
}
```

```
void transfervalue(int op)
{
        int p;
        for(p =0;p<cubnum - 1; p++){
                if(balls[p].return_protect == 1){
                        balls[p].bx = balls[p].ret_bx;
                        balls[p].by = balls[p].ret_by;
                        balls[p].bz = balls[p].ret_bz;
                        balls[p].plane_num = balls[p].ret_direct;
                        balls[p].return_protect = 0;
                }
        }
        switch(op)
        {
                case 1:
                        {
                                if(x_angle_l>=256 - rotation_rate){
                                        x_angle_l = x_angle_l + rotation_rate - 256;
                                        message[0] = message[0] + rotation_rate;
                                        if(x_angle_h == 15)
                                        {
                                                x_angle_h = 0;
                                                message[1] = 0x00;
                                        }
                                        else
                                        {
                                                x_angle_h++;
                                                message[1] = message[1]+1;
                                        }
                                }
                                else
                                {
                                        x_angle_l+=rotation_rate;
                                        message[0] = message[0]+rotation_rate;
                                }
                                break;
                        }
                case 2:
                        {
                                if(x_angle_l<=rotation_rate - 1){
                                        x_angle_l = x_angle_l + 256 - rotation_rate;
                                        message[0] = message[0] - rotation_rate;
                        if(x_angle_h == 0)
                        {
                                x_angle_h = 15;
                                message[1] = 0x0F;
                        }
                        else
                        {
                                x_angle_h--;
                                message[1] = message[1]-1;
                        }
                }
                else
                {
                        x_angle_l-=rotation_rate;
                        message[0] = message[0]-rotation_rate;
                }
                break;
        }

case 3:
        {

                if(y_angle_l>=256 - rotation_rate){
                        y_angle_l = y_angle_l + rotation_rate - 256;
                        message[2] = message[2] + rotation_rate;
                        if(y_angle_h == 15)
                        {
                                y_angle_h = 0;
                                message[3] = 0x00;
                        }
                        else
                        {
                                y_angle_h++;
                                message[3] = message[3]+1;
                        }
                }
                else
                {
                        y_angle_l+=rotation_rate;
                        message[2] = message[2]+rotation_rate;
                }
                break;
        }
case 4:
```

```
                        {
                                if(y_angle_l<=rotation_rate - 1){
                                        y_angle_l = y_angle_l + 256 - rotation_rate;
                                        message[2] = message[2] - rotation_rate;
                                        if(y_angle_h == 0)
                                        {
                                                y_angle_h = 15;
                                                message[3] = 0x0F;
                                        }
                                        else
                                        {
                                                y_angle_h--;
                                                message[3] = message[3]-1;
                                        }
                                }
                                else
                                {
                                        y_angle_l-=rotation_rate;
                                        message[2] = message[2]-rotation_rate;
                                }
                                break;
                        }

                case 5:
                        {
                                ball_reach[0] = 0;
                                        ball_reach[1] = 0;
                                        ball_reach[2] = 0;
                                        ball_reach[3] = 0;
                                initialize_ball();
                                break;
                        }
                break;
        }
        write_segments(message);
        if(message[4] = 0x01)message[4] = 0x00;
    return NULL;
}




void combine_ball(int i, int j){
			if(abs(balls[i].bx - balls[j].bx)<=1&&abs(balls[i].by - balls[j].by)<=1&&abs(balls[i].bz
- balls[j].bz)<=1)
			{

				balls[j].b_dict = balls[i].b_dict;
				balls[j].next_jump_p = balls[i].next_jump_p;
				balls[j].jump_x = balls[i].jump_x;
				balls[j].jump_y = balls[i].jump_y;
				balls[j].jump_z = balls[i].jump_z;
				balls[j].jump_Node = balls[i].jump_Node;
				balls[j].prior_plane = balls[i].prior_plane;
				balls[j].prior_direct = balls[i].prior_direct;
				balls[j].next_is_edge = balls[i].next_is_edge;
				balls[j].edge_plane_num = balls[i].edge_plane_num;
				balls[j].ret_bx = balls[i].ret_bx;
				balls[j].ret_by = balls[i].ret_by;
				balls[j].ret_bz = balls[i].ret_bz;
				balls[j].return_protect = balls[i].return_protect;
				balls[j].ret_direct = balls[i].ret_direct;
			}
}
```

Vga_led.c

```
/*
 * Device driver for the VGA LED Emulator
 *
 * A Platform device implemented using the misc subsystem
 *
 * Stephen A. Edwards
 * Columbia University
 *
 * References:
 * Linux source: Documentation/driver-model/platform.txt
 *                drivers/misc/arm-charlcd.c
 * http://www.linuxforu.com/tag/linux-device-drivers/
 * http://free-electrons.com/docs/
 *
 * "make" to build
 * insmod vga_led.ko
 *
 * Check code style with
 * checkpatch.pl --file --no-tree vga_led.c
 */
```

```
#include <linux/module.h>
#include <linux/init.h>
#include <linux/errno.h>
#include <linux/version.h>
#include <linux/kernel.h>
#include <linux/platform_device.h>
#include <linux/miscdevice.h>
#include <linux/slab.h>
#include <linux/io.h>
#include <linux/of.h>
#include <linux/of_address.h>
#include <linux/fs.h>
#include <linux/uaccess.h>
#include "vga_led.h"

#define DRIVER_NAME "vga_led"

/*
 * Information about our device dsfhsdjkfaskjfgdsakj
 */
struct vga_led_dev {
	struct resource res; /* Resource: our registers */
	void __iomem *virtbase; /* Where registers can be accessed in memory */
	int segments[VGA_LED_DIGITS];
} dev;

/*
 * Write segments of a single digit
 * Assumes digit is in range and the device information has been set up
 */
static void write_digit(int digit, int segments)
{
	iowrite8(segments, dev.virtbase + digit);
	dev.segments[digit] = segments;
}

/*
 * Handle ioctl() calls from userspace:
 * Read or write the segments on single digits.
 * Note extensive error checking of arguments
 */
static long vga_led_ioctl(struct file *f, unsigned int cmd, unsigned long arg)
{
	vga_led_arg_t vla;

	switch (cmd) {
	case VGA_LED_WRITE_DIGIT:
		if (copy_from_user(&vla, (vga_led_arg_t *) arg,
				   sizeof(vga_led_arg_t)))
			return -EACCES;
		if (vla.digit > 64)		//	modified by ly
			return -EINVAL;
		write_digit(vla.digit, vla.segments);
		break;

	case VGA_LED_READ_DIGIT:
		if (copy_from_user(&vla, (vga_led_arg_t *) arg,
				   sizeof(vga_led_arg_t)))
			return -EACCES;
		if (vla.digit > 64)		//	modified by ly
			return -EINVAL;
		vla.segments = dev.segments[vla.digit];
		if (copy_to_user((vga_led_arg_t *) arg, &vla,
				 sizeof(vga_led_arg_t)))
			return -EACCES;
		break;

	default:
		return -EINVAL;
	}

	return 0;
}

/* The operations our device knows how to do */
static const struct file_operations vga_led_fops = {
	.owner		= THIS_MODULE,
	.unlocked_ioctl = vga_led_ioctl,
};

/* Information about our device for the "misc" framework -- like a char dev */
static struct miscdevice vga_led_misc_device = {
	.minor		= MISC_DYNAMIC_MINOR,
	.name		= DRIVER_NAME,
	.fops	= &vga_led_fops,
};
```

```
/*
 * Initialization code: get resources (registers) and display
 * a welcome message
 */
static int __init vga_led_probe(struct platform_device *pdev)
{

/*    modified by ly    */

        static unsigned char welcome_message[VGA_LED_DIGITS] = {
                0x3E, 0x7D, 0x77, 0x08, 0x38, 0x79, 0x5E, 0x00,
                0x3E, 0x7D, 0x77, 0x08, 0x38, 0x79, 0x5E, 0x00};
        int i, ret;

/*    modified by ly    */

        /* Register ourselves as a misc device: creates /dev/vga_led */
        ret = misc_register(&vga_led_misc_device);

        /* Get the address of our registers from the device tree */
        ret = of_address_to_resource(pdev->dev.of_node, 0, &dev.res);
        if (ret) {
                ret = -ENOENT;
                goto out_deregister;
        }

        /* Make sure we can use these registers */
        if (request_mem_region(dev.res.start, resource_size(&dev.res),
                               DRIVER_NAME) == NULL) {
                ret = -EBUSY;
                goto out_deregister;
        }

        /* Arrange access to our registers */
        dev.virtbase = of_iomap(pdev->dev.of_node, 0);
        if (dev.virtbase == NULL) {
                ret = -ENOMEM;
                goto out_release_mem_region;
        }

        /* Display a welcome message */
        for (i = 0; i < VGA_LED_DIGITS; i++)
                write_digit(i, welcome_message[i]);
        return 0;

out_release_mem_region:
        release_mem_region(dev.res.start, resource_size(&dev.res));
out_deregister:
        misc_deregister(&vga_led_misc_device);
        return ret;
}

/* Clean-up code: release resources */
static int vga_led_remove(struct platform_device *pdev)
{
        iounmap(dev.virtbase);
        release_mem_region(dev.res.start, resource_size(&dev.res));
        misc_deregister(&vga_led_misc_device);
        return 0;
}

/* Which "compatible" string(s) to search for in the Device Tree */
#ifdef CONFIG_OF
static const struct of_device_id vga_led_of_match[] = {
        { .compatible = "altr,vga_led" },
        {},
};
MODULE_DEVICE_TABLE(of, vga_led_of_match);
#endif

/* Information for registering ourselves as a "platform" driver */
static struct platform_driver vga_led_driver = {
        .driver     = {
                .name      = DRIVER_NAME,
                .owner     = THIS_MODULE,
                .of_match_table = of_match_ptr(vga_led_of_match),
        },
        .remove   = __exit_p(vga_led_remove),
};

/* Called when the module is loaded: set things up */
static int __init vga_led_init(void)
{
        pr_info(DRIVER_NAME ": init\n");
        return platform_driver_probe(&vga_led_driver, vga_led_probe);
}
```

```
/* Called when the module is unloaded: release resources */
static void __exit vga_led_exit(void)
{
        platform_driver_unregister(&vga_led_driver);
        pr_info(DRIVER_NAME ": exit\n");
}

module_init(vga_led_init);
module_exit(vga_led_exit);

MODULE_LICENSE("GPL");
MODULE_AUTHOR("Stephen A. Edwards, Columbia University");
MODULE_DESCRIPTION("VGA 7-segment LED Emulator");
```

Vga_led.h

```
#ifndef _VGA_LED_H
#define _VGA_LED_H

#include <linux/ioctl.h>

#define VGA_LED_DIGITS 64

typedef struct {
    unsigned char digit;        /* 0, 1, .. , VGA_LED_DIGITS - 1 */
    unsigned char segments; /* LSB is segment a, MSB is decimal point */
} vga_led_arg_t;

#define VGA_LED_MAGIC 'q'

/* ioctls and their arguments */
#define VGA_LED_WRITE_DIGIT _IOW(VGA_LED_MAGIC, 1, vga_led_arg_t *)
#define VGA_LED_READ_DIGIT    _IOWR(VGA_LED_MAGIC, 2, vga_led_arg_t *)

#endif
```

Makefile

```
CFLAGS = -Wall

OBJECTS = hello.o usbkeyboard.o

TARFILES = Makefile hello.c \
	usbkeyboard.h usbkeyboard.c

hello : $(OBJECTS)
	cc $(CFLAGS) -o hello $(OBJECTS) -lusb-1.0 -pthread -lm

hello.tar.gz : $(TARFILES)
	rm -rf hello
	mkdir hello
	ln $(TARFILES) hello
	tar zcf hello.tar.gz hello
	rm -rf hello

hello.o : hello.c usbkeyboard.h
usbkeyboard.o : usbkeyboard.c usbkeyboard.h -lm

.PHONY : clean
clean :
	rm -rf *.o hello
```

Hardware

Miffilegen.m

```
function [outfname, rows, cols] = miffilegen_v2(infile,outfname, numrows, numcols)

img = imread(infile);

imgresized = imresize(img, [numrows numcols]);

[rows, cols, rgb] = size(imgresized);

imgscaled = imgresized;
imshow(imgscaled);

fid = fopen(outfname,'w');

fprintf(fid,'-- %3ux%3u 24bit image color values\n\n',rows,cols);
fprintf(fid,'WIDTH = 24;\n');
fprintf(fid,'DEPTH = %4u;\n\n',rows*cols);
fprintf(fid,'ADDRESS_RADIX = UNS;\n');
fprintf(fid,'DATA_RADIX = UNS;\n\n');
fprintf(fid,'CONTENT BEGIN\n');
```

```
count = 0;
for r = 1:rows
        for c = 1:cols
                red = uint32(imgscaled(r,c,1));
                green = uint32(imgscaled(r,c,2));
                blue = uint32(imgscaled(r,c,3));
                color = red*(65536) + green*(256) + blue;
                fprintf(fid,'%4u : %u;\n',count, color);
                count = count + 1;
        end
end
fprintf(fid,'END;');
fclose(fid);
```

Sin_Cos_LUT.m

```
clc;clear;
N = 10;
depth=2^N;
widths=N;
index = linspace(0,pi*2,depth);
sin_value = cos(index);
%sin_value = sin_value * (depth/2 -1);
sin_value = sin_value * (depth);
sin_value = fix((sin_value)+0.5);
%plot(sin_value);
number = [0:depth];
fid=fopen('Sine_ROM.mif','w+');
fprintf(fid,'depth=%d;\n',depth);
fprintf(fid,'width=%d;\n',widths);
fprintf(fid,'address_radix=UNS;\n');
fprintf(fid,'data_radix = DEC;\n');
fprintf(fid,'Content Begin\n');
for i = 1 : depth
        fprintf(fid, '%d\t:\t%d;\r\n', number(i),sin_value(i));
end
fprintf(fid,'end;');
fclose(fid);
```

Vga_led.sv

```
module VGA_LED_Emulator(
  input logic               clk50, reset,
  input logic [7:0]    hex0, hex1, hex2, hex3, hex4, hex5, hex6, hex7, hex8, hex9,
                                          hex10, hex11, hex12, hex13, hex14, hex15, hex16, hex17, hex18,
hex19,
                                          hex20, hex21, hex22, hex23, hex24, hex25, hex26, hex27, hex28,
hex29,
                                          hex30, hex31, hex32, hex33, hex34, hex35, hex36, hex37, hex38,
hex39,
                                          hex40, hex41, hex42, hex43, hex44, hex45, hex46, hex47, hex48,
hex49,
                                          hex50, hex51, hex52, hex53, hex54, hex55, hex56, hex57, hex58,
hex59,
  output logic [7:0] VGA_R, VGA_G, VGA_B,
  output logic          VGA_CLK, VGA_HS, VGA_VS, VGA_BLANK_n, VGA_SYNC_n);

/*
  * 640 X 480 VGA timing for a 50 MHz clock: one pixel every other cycle
  *
  *HCOUNT 1599 0                    1279            1599 0
  *                   _________________                  _________
  * ___________|        Video            |_____________|    Video
  *
  *
  * |SYNC| BP |<-- HACTIVE -->|FP|SYNC| BP |<-- HACTIVE
  *            __________________________        ______________
  * |____|              VGA_HS                   |____|
  */

      parameter radius_square = 20'd 1024;

    parameter HACTIVE          = 11'd 1280,
                  HFRONT_PORCH = 11'd 32,
                  HSYNC              = 11'd 192,
                  HBACK_PORCH    = 11'd 96,
                  HTOTAL             = HACTIVE + HFRONT_PORCH + HSYNC + HBACK_PORCH; //1600

    parameter VACTIVE          = 10'd 480,
                  VFRONT_PORCH = 10'd 10,
                  VSYNC              = 10'd 2,
                  VBACK_PORCH    = 10'd 33,
                  VTOTAL             = VACTIVE + VFRONT_PORCH + VSYNC + VBACK_PORCH; //525

    logic [10:0]                          hcount; // Horizontal counter
    logic                        endOfLine;
    always_ff @(posedge clk50 or posedge reset)
      if (reset)                hcount <= 0;
      else if (endOfLine) hcount <= 0;
      else                      hcount <= hcount + 11'd 1;

    assign endOfLine = hcount == HTOTAL - 1;


    // Vertical counter
    logic [9:0]                         vcount;
     logic[9:0]            vcount_plus1;
    logic                       endOfField;

    always_ff @(posedge clk50 or posedge reset)
      if (reset)                vcount <= 0;
      else if (endOfLine)
        if (endOfField)     vcount <= 0;
        else                      vcount <= vcount + 10'd 1;

    assign endOfField = vcount == VTOTAL - 1;

    // Horizontal sync: from 0x520 to 0x57F
    // 101 0010 0000 to 101 0111 1111
    assign VGA_HS = !( (hcount[10:7] == 4'b1010) & (hcount[6] | hcount[5]));
    assign VGA_VS = !( vcount[9:1] == (VACTIVE + VFRONT_PORCH) / 2);

    assign VGA_SYNC_n = 1; // For adding sync to video signals; not used for VGA

    // Horizontal active: 0 to 1279         Vertical active: 0 to 479
    // 101 0000 0000    1280              01 1110 0000    480
    // 110 0011 1111    1599              10 0000 1100    524
    assign VGA_BLANK_n = !( hcount[10] & (hcount[9] | hcount[8]) ) &
                 !( vcount[9] | (vcount[8:5] == 4'b1111) );

    assign VGA_CLK = hcount[0]; // 25 MHz clock: pixel latched on rising edge




//////////////////////////
/*        added by cong         */
```

```
//////////////////////////
            logic                   inEdge;
            logic                   insurface;
            logic                   inBall_1;
            logic                   inBall_2;
            logic                   inBall_3;
            logic                   inBall_4;
            logic                   inHole;
            logic                   inEndPoint;
            logic                   shelter;
            logic [10:0]        hcount_s;

            logic                   hitSurface_s1;
            logic                   hitSurface_s2;
            logic                   hitSurface_s3;
            logic                   hitSurface_s4;
            logic                   hitSurface_s5;

            logic                   hitEdge_s1;
            logic                   hitEdge_s2;
            logic                   hitEdge_s3;
            logic                   hitEdge_s4;
            logic                   hitEdge_s5;

            logic                   hitSurface_b;
//////////////////////////
/*          Framebuffer         */
//////////////////////////
            logic                   fb_odd_wren;
            logic[127:0]        fb_odd_out;
            integer                 fb_odd_waddr;
            integer                 fb_odd_raddr;
            integer                 fb_odd_addr;

            logic                   fb_even_wren;
            logic[127:0]        fb_even_out;
            integer                 fb_even_waddr;
            integer                 fb_even_raddr;
            integer                 fb_even_addr;

/////////////////////////
//   Space    information    //
/////////////////////////
            integer                 x;
```

```
        integer             y;
        integer             z;
        integer             x_r1;
        integer             y_r1;
        integer             z_r1;
        integer             x_r2;
        integer             y_r2;
        integer             z_r2;
        integer             x0;

        integer             sin__x;
        integer             cos__x;
        integer             sin__y;
        integer             cos__y;

        integer             scan_count;
        integer             vcount_integer;
        integer             hcount_s_pack;
        integer             hcount_s_surface;
        integer             hcount_s_edge;
        integer             hcount_s_ball_1;
        integer             hcount_s_ball_2;
        integer             hcount_s_ball_3;
        integer             hcount_s_ball_4;
        integer             hcount_s_hole;
        integer             hcount_s_endPoint;

        reg [15:0][7:0] plane;
        logic[127:0]        plane_r;
        reg [3:0]           section_sel = 4'b0;

////////////////////////////
//    object information    //
////////////////////////////

//    square one
        integer   x1_s1;
        integer   x2_s1;
        integer   y1_s1;
        integer   y2_s1;
        integer   z1_s1;
        integer   z2_s1;

//    square two
```

```
           integer    x1_s2;
           integer    x2_s2;
           integer    y1_s2;
           integer    y2_s2;
           integer    z1_s2;
           integer    z2_s2;

//    square three
           integer    x1_s3;
           integer    x2_s3;
           integer    y1_s3;
           integer    y2_s3;
           integer    z1_s3;
           integer    z2_s3;

//    square four
           integer    x1_s4;
           integer    x2_s4;
           integer    y1_s4;
           integer    y2_s4;
           integer    z1_s4;
           integer    z2_s4;

//    square five
           integer    x1_s5;
           integer    x2_s5;
           integer    y1_s5;
           integer    y2_s5;
           integer    z1_s5;
           integer    z2_s5;

//    end point
           integer    x_ep;
           integer    x1_ep;
           integer    x2_ep;
           integer    y_ep;
           integer    z_ep;
           integer    z1_ep;
           integer    z2_ep;

//    ball one
           integer    x_b1;
           integer    y_b1;
           integer    z_b1;
```

```
            integer    x1_b1;
            integer    y1_b1;
            integer    z1_b1;
            integer    x2_b1;
            integer    y2_b1;
            integer    z2_b1;

//    ball two
            integer    x_b2;
            integer    y_b2;
            integer    z_b2;
            integer    x1_b2;
            integer    y1_b2;
            integer    z1_b2;
            integer    x2_b2;
            integer    y2_b2;
            integer    z2_b2;

//    ball three
            integer    x_b3;
            integer    y_b3;
            integer    z_b3;
            integer    x1_b3;
            integer    y1_b3;
            integer    z1_b3;
            integer    x2_b3;
            integer    y2_b3;
            integer    z2_b3;

//    ball four
            integer    x_b4;
            integer    y_b4;
            integer    z_b4;
            integer    x1_b4;
            integer    y1_b4;
            integer    z1_b4;
            integer    x2_b4;
            integer    y2_b4;
            integer    z2_b4;
//////////////////////////
/*ball select information*/
//////////////////////////
            reg[1:0]         ball_select;
            integer     x1_b;
            integer     y1_b;
            integer     z1_b;
            integer     x2_b;
            integer     y2_b;
            integer     z2_b;

////////////////////
/*state information*/
////////////////////
            logic       start = 1'b0;
            logic       gameover;

/////////////////////
/* set object value */
/////////////////////

//    end point
            assign      x_ep = {{24{hex7[7]}}, hex7};
            assign      y_ep = {{24{hex8[7]}}, hex8};
            assign      z_ep = {{24{hex9[7]}}, hex9};
            assign      x1_ep = x_ep - 5;
            assign      x2_ep = x_ep + 5;
            assign      z1_ep = z_ep - 5;
            assign      z2_ep = z_ep + 5;

//    square one
            assign      x1_s1 = {{24{hex10[7]}}, hex10};//-50;
            assign      x2_s1 = {{24{hex11[7]}}, hex11};//-40;
            assign      y1_s1 = {{24{hex12[7]}}, hex12};//-50;
            assign      y2_s1 = {{24{hex13[7]}}, hex13};//-40;
            assign      z1_s1 = {{24{hex14[7]}}, hex14};//-50;
            assign      z2_s1 = {{24{hex15[7]}}, hex15};//50;

//    square two
            assign      x1_s2 = {{24{hex16[7]}}, hex16};//-40;
            assign      x2_s2 = {{24{hex17[7]}}, hex17};//20;
            assign      y1_s2 = {{24{hex18[7]}}, hex18};//40;
            assign      y2_s2 = {{24{hex19[7]}}, hex19};//50;
            assign      z1_s2 = {{24{hex20[7]}}, hex20};//-50;
            assign      z2_s2 = {{24{hex21[7]}}, hex21};//-40;

//    square three
            assign      x1_s3 = {{24{hex22[7]}}, hex22};//40;
            assign      x2_s3 = {{24{hex23[7]}}, hex23};//50;
            assign      y1_s3 = {{24{hex24[7]}}, hex24};//0;
            assign      y2_s3 = {{24{hex25[7]}}, hex25};//10;
            assign      z1_s3 = {{24{hex26[7]}}, hex26};//-10;
            assign      z2_s3 = {{24{hex27[7]}}, hex27};//50;

//    square four
            assign      x1_s4 = {{24{hex28[7]}}, hex28};//-20;
            assign      x2_s4 = {{24{hex29[7]}}, hex29};//50;
            assign      y1_s4 = {{24{hex30[7]}}, hex30};//-20;
            assign      y2_s4 = {{24{hex31[7]}}, hex31};//-10;
            assign      z1_s4 = {{24{hex32[7]}}, hex32};//40;
            assign      z2_s4 = {{24{hex33[7]}}, hex33};//50;

//    square five
            assign      x1_s5 = {{24{hex34[7]}}, hex34};//-50;
            assign      x2_s5 = {{24{hex35[7]}}, hex35};//20;
            assign      y1_s5 = {{24{hex36[7]}}, hex36};//-20;
            assign      y2_s5 = {{24{hex37[7]}}, hex37};//-10;
            assign      z1_s5 = {{24{hex38[7]}}, hex38};//0;
            assign      z2_s5 = {{24{hex39[7]}}, hex39};//10;

//      ball one
            assign      x_b1 = {{24{hex40[7]}}, hex40};
            assign      y_b1 = {{24{hex41[7]}}, hex41};
            assign      z_b1 = {{24{hex42[7]}}, hex42};
            assign      x1_b1 = x_b1 - 4;
            assign      y1_b1 = y_b1 - 4;
            assign      z1_b1 = z_b1 - 4;
            assign      x2_b1 = x_b1 + 4;
            assign      y2_b1 = y_b1 + 4;
            assign      z2_b1 = z_b1 + 4;

//    ball two
            assign      x_b2 = {{24{hex43[7]}}, hex43};
            assign      y_b2 = {{24{hex44[7]}}, hex44};
            assign      z_b2 = {{24{hex45[7]}}, hex45};
            assign      x1_b2 = x_b2 - 4;
            assign      y1_b2 = y_b2 - 4;
            assign      z1_b2 = z_b2 - 4;
            assign      x2_b2 = x_b2 + 4;
            assign      y2_b2 = y_b2 + 4;
            assign      z2_b2 = z_b2 + 4;
```

```
//    ball three
          assign      x_b3 = {{24{hex46[7]}}, hex46};
          assign      y_b3 = {{24{hex47[7]}}, hex47};
          assign      z_b3 = {{24{hex48[7]}}, hex48};
          assign      x1_b3 = x_b3 - 4;
          assign      y1_b3 = y_b3 - 4;
          assign      z1_b3 = z_b3 - 4;
          assign      x2_b3 = x_b3 + 4;
          assign      y2_b3 = y_b3 + 4;
          assign      z2_b3 = z_b3 + 4;

//    ball four
          assign      x_b4 = {{24{hex49[7]}}, hex49};
          assign      y_b4 = {{24{hex50[7]}}, hex50};
          assign      z_b4 = {{24{hex51[7]}}, hex51};
          assign      x1_b4 = x_b4 - 4;
          assign      y1_b4 = y_b4 - 4;
          assign      z1_b4 = z_b4 - 4;
          assign      x2_b4 = x_b4 + 4;
          assign      y2_b4 = y_b4 + 4;
          assign      z2_b4 = z_b4 + 4;

/////////////////////////////////////////////////////
/*                    Control Signal                    */
/////////////////////////////////////////////////////
          assign hcount_s = hcount - 11'd128;

          assign hcount_s_pack = hcount_s[5:1] - 1'b1;
          assign hcount_s_surface = {hcount_s_pack[4:1], 3'd0};
          assign hcount_s_edge = {hcount_s_pack[4:1], 3'd1};
          assign hcount_s_ball_1 = {hcount_s_pack[4:1], 3'd2};
          assign hcount_s_ball_2 = {hcount_s_pack[4:1], 3'd3};
          assign hcount_s_ball_3 = {hcount_s_pack[4:1], 3'd4};
          assign hcount_s_ball_4 = {hcount_s_pack[4:1], 3'd5};
          assign hcount_s_hole = {hcount_s_pack[4:1], 3'd6};
          assign hcount_s_endPoint = {hcount_s_pack[4:1], 3'd7};

          assign fb_odd_wren     = !vcount[1] && (hcount_s == 11'd290 || hcount_s == 11'd590
|| hcount_s == 11'd890 || hcount_s == 11'd1190);
          assign fb_even_wren    =   vcount[1] && (hcount_s == 11'd290 || hcount_s == 11'd590
|| hcount_s == 11'd890 || hcount_s == 11'd1190);
          assign fb_odd_waddr    = {section_sel, vcount[8:2]};
          assign fb_odd_raddr    = {hcount_s[9:6], vcount[8:2]};
          assign fb_even_waddr = {section_sel, vcount[8:2] + 7'd1};
```

```
	assign fb_even_raddr = {hcount_s[9:6], vcount[8:2]};
	assign fb_odd_addr	= fb_odd_wren	? fb_odd_waddr	: fb_odd_raddr;
	assign fb_even_addr	= fb_even_wren ? fb_even_waddr : fb_even_raddr;

	assign insurface = vcount[1] ? fb_odd_out[hcount_s_surface] :
fb_even_out[hcount_s_surface];
	assign inEdge = vcount[1] ? fb_odd_out[hcount_s_edge] : fb_even_out[hcount_s_edge];
	assign inBall_1 = vcount[1] ? fb_odd_out[hcount_s_ball_1] :
fb_even_out[hcount_s_ball_1];
	assign inBall_2 = vcount[1] ? fb_odd_out[hcount_s_ball_2] :
fb_even_out[hcount_s_ball_2];
	assign inBall_3 = vcount[1] ? fb_odd_out[hcount_s_ball_3] :
fb_even_out[hcount_s_ball_3];
	assign inBall_4 = vcount[1] ? fb_odd_out[hcount_s_ball_4] :
fb_even_out[hcount_s_ball_4];
	assign inHole = vcount[1] ? fb_odd_out[hcount_s_hole] : fb_even_out[hcount_s_hole];
	assign inEndPoint = vcount[1] ? fb_odd_out[hcount_s_endPoint] :
fb_even_out[hcount_s_endPoint];

	assign shelter = hcount_s[10] || hcount_s[10:2] == 9'd0;

	assign x1_b = ball_select == 0 ? x1_b1 :
			ball_select == 1 ? x1_b2 :
			ball_select == 2 ? x1_b3 :
					x1_b4;
	assign y1_b = ball_select == 0 ? y1_b1 :
			ball_select == 1 ? y1_b2 :
			ball_select == 2 ? y1_b3 :
					y1_b4;
	assign z1_b = ball_select == 0 ? z1_b1 :
			ball_select == 1 ? z1_b2 :
			ball_select == 2 ? z1_b3 :
					z1_b4;

	assign x2_b = ball_select == 0 ? x2_b1 :
			ball_select == 1 ? x2_b2 :
			ball_select == 2 ? x2_b3 :
					x2_b4;
	assign y2_b = ball_select == 0 ? y2_b1 :
			ball_select == 1 ? y2_b2 :
			ball_select == 2 ? y2_b3 :
					y2_b4;
	assign z2_b = ball_select == 0 ? z2_b1 :
			ball_select == 1 ? z2_b2 :
```

```
                                    ball_select == 2 ? z2_b3 :
                                                   z2_b4;
////////////////////////////////////////////////////
/*                      Buffer Mapping                      */
////////////////////////////////////////////////////
        genvar i,j;
        generate
            for(j=0; j<16; j=j+1)
            begin:plane_buffer_mapping_loop1
                for(i=0; i<8; i=i+1)
                begin: plane_buffer_mapping_loop2
                    assign plane_r[8*j + i] = plane[j][i];
                end
            end
        endgenerate

////////////////////////////////////////////////////
/*                      Function & Task                      */
////////////////////////////////////////////////////
        function hitSurface;
            input integer x_r, y_r, z_r, x1_s, x2_s, y1_s, y2_s, z1_s, z2_s;
            begin
                hitSurface = (x_r == x1_s || x_r == x2_s) && y_r >= y1_s && y_r <= y2_s &&
z_r >= z1_s && z_r <= z2_s ||
                                    (y_r == y1_s || y_r == y2_s) && z_r >= z1_s && z_r <=
z2_s && x_r >= x1_s && x_r <= x2_s ||
                                    (z_r == z1_s || z_r == z2_s) && x_r >= x1_s && x_r <= x2_s
&& y_r >= y1_s && y_r <= y2_s;
            end
        endfunction

        function hitEdge;
            input integer x_r, y_r, z_r, x1_s, x2_s, y1_s, y2_s, z1_s, z2_s;
            begin
                hitEdge = (x_r == x1_s || x_r == x2_s) && (y_r == y1_s || y_r == y2_s) && z_r >=
z1_s && z_r <= z2_s ||
                                (y_r == y1_s || y_r == y2_s) && (z_r == z1_s || z_r == z2_s) &&
x_r >= x1_s && x_r <= x2_s ||
                                (z_r == z1_s || z_r == z2_s) && (x_r == x1_s || x_r == x2_s) &&
y_r >= y1_s && y_r <= y2_s;
            end
        endfunction

////////////////////////////////////////////////////
```

```
/*                              sequential logic                              */
///////////////////////////////////////////////////
            always_ff @(posedge clk50) begin
            //ball select
                  ball_select = ball_select + 2'b1;

                  start <= ((hex4[0] == 1'b1)&&gameover);

            //initial
                  if (hcount_s == 11'd0 || hcount_s == 11'd300 || hcount_s == 11'd600 || hcount_s
== 11'd900) begin
                        scan_count <= 0;
                        section_sel[2:0] <= section_sel[2:0] + 3'b1;
                        for (x = 0; x < 16; x++) plane[x] <= 8'b0;
                  end

                  if (endOfLine && endOfField) begin
                        section_sel[3] <= !section_sel[3];
                  end

                  if (scan_count != 256) begin
                        scan_count <= scan_count + 1;
                        for (x = 0; x < 16; x++) begin
                                    x0 = {24'b0,section_sel, x[3:0]} - 128;

                                    x_r1 = x0;
                                    y_r1 = ((cos__x*y + sin__x*z)>>>12);
                                    z_r1 = ((-sin__x*y + cos__x*z)>>>12);

                                    x_r2 = ((-sin__y*z_r1 + cos__y*x_r1)>>>12);
                                    y_r2 = y_r1;
                                    z_r2 = ((cos__y*z_r1 + sin__y*x_r1)>>>12);

                                    hitSurface_b = hitSurface(x_r2, y_r2, z_r2, x1_b, x2_b, y1_b, y2_b,
z1_b, z2_b);

                                    hitSurface_s1 = hitSurface(x_r2, y_r2, z_r2, x1_s1, x2_s1, y1_s1,
y2_s1, z1_s1, z2_s1);
                                    hitSurface_s2 = hitSurface(x_r2, y_r2, z_r2, x1_s2, x2_s2, y1_s2,
y2_s2, z1_s2, z2_s2);
                                    hitSurface_s3 = hitSurface(x_r2, y_r2, z_r2, x1_s3, x2_s3, y1_s3,
y2_s3, z1_s3, z2_s3);
                                    hitSurface_s4 = hitSurface(x_r2, y_r2, z_r2, x1_s4, x2_s4, y1_s4,
y2_s4, z1_s4, z2_s4);
```

```
                        hitSurface_s5 = hitSurface(x_r2, y_r2, z_r2, x1_s5, x2_s5, y1_s5,
y2_s5, z1_s5, z2_s5);

                        hitEdge_s1 = hitEdge(x_r2, y_r2, z_r2, x1_s1, x2_s1, y1_s1, y2_s1,
z1_s1, z2_s1);
                        hitEdge_s2 = hitEdge(x_r2, y_r2, z_r2, x1_s2, x2_s2, y1_s2, y2_s2,
z1_s2, z2_s2);
                        hitEdge_s3 = hitEdge(x_r2, y_r2, z_r2, x1_s3, x2_s3, y1_s3, y2_s3,
z1_s3, z2_s3);
                        hitEdge_s4 = hitEdge(x_r2, y_r2, z_r2, x1_s4, x2_s4, y1_s4, y2_s4,
z1_s4, z2_s4);
                        hitEdge_s5 = hitEdge(x_r2, y_r2, z_r2, x1_s5, x2_s5, y1_s5, y2_s5,
z1_s5, z2_s5);

                        if (plane[x] == 8'b0) plane[x][0] <= hitSurface_s1 ||     hitSurface_s2
|| hitSurface_s3 || hitSurface_s4 || hitSurface_s5;

                        if (plane[x] == 8'b0) plane[x][1] <= hitEdge_s1 ||  hitEdge_s2        ||
hitEdge_s3 || hitEdge_s4 || hitEdge_s5;// || ball_edge;

                        if (plane[x] == 8'b0) plane[x][6] <= hex5[0] && hitSurface_s1 ||
hex5[1] && hitSurface_s2 || hex5[2] && hitSurface_s3 ||
                                                                                    hex5[3]
&& hitSurface_s4 || hex5[4] && hitSurface_s5;

                        if (plane[x] == 8'b0) plane[x][7] <= x_r2 >= x1_ep && x_r2 <= x2_ep
&& y_r2 == y_ep && z_r2 >= z1_ep && z_r2 <= z2_ep;

                        if (plane[x] == 8'b0 && ball_select == 2'd0) plane[x][2] <=
hitSurface_b;

                        if (plane[x] == 8'b0 && ball_select == 2'd1) plane[x][3] <=
hitSurface_b;
//

                        if (plane[x] == 8'b0 && ball_select == 2'd2) plane[x][4] <=
hitSurface_b;

                        if (plane[x] == 8'b0 && ball_select == 2'd3) plane[x][5] <=
hitSurface_b;

                end
            end
        end
```

```
sin_x sinx(.address(address_sinx), .clock(clk50), .q(sin__x));
cos_x cosx(.address(address_cosx), .clock(clk50), .q(cos__x));
sin_y siny(.address(address_siny), .clock(clk50), .q(sin__y));
cos_y cosy(.address(address_cosy), .clock(clk50), .q(cos__y));


FrameBuffer fb_odd(     .address(fb_odd_addr),
                                .clock(clk50),
                                .data(plane_r),
                                .wren(fb_odd_wren),
                                .q(fb_odd_out));

FrameBuffer fb_even(    .address(fb_even_addr),
                                .clock(clk50),
                                .data(plane_r),
                                .wren(fb_even_wren),
                                .q(fb_even_out));

logic [11:0]                    address_sinx;
logic [11:0]                    address_cosx;
logic [11:0]                    address_siny;
logic [11:0]                    address_cosy;

logic [29:0]                    gameover_counter = 30'b0;
logic [1:0]                     state, next;
logic                                   flash = 1'b0;
logic [5:0]                             flash_counter = 6'b0;

always_ff @(posedge clk50)
if(gameover)
        gameover_counter <= gameover_counter + 1'b1;
else
        gameover_counter <= 1'b0;


assign address_sinx = gameover ? gameover_counter[29:18] : {hex3[3:0],hex2};
assign address_cosx = gameover ? gameover_counter[29:18] : {hex3[3:0],hex2};
assign address_siny = gameover ? gameover_counter[29:18] : {hex1[3:0],hex0};
assign address_cosy = gameover ? gameover_counter[29:18] : {hex1[3:0],hex0};

assign gameover = hex6[0];
```

```
    always_comb begin
        vcount_integer = vcount[9:1];
        y = vcount_integer - 128;
        z = scan_count - 128;
        {VGA_R, VGA_G, VGA_B} = flash ? {8'hff, 8'hff, 8'hff} : {8'h0, 8'h0, 8'h0}; // black

            case (gameover)
            1'b0: begin
                if (insurface) {VGA_R, VGA_G, VGA_B} = {8'hff, 8'hff, 8'hff}; // white
                if (inHole) {VGA_R, VGA_G, VGA_B} = {8'hff, 8'hff, 8'h66}; // golden

                if (inEndPoint) {VGA_R, VGA_G, VGA_B} = {8'hff, 8'hff, 8'h0};
                if (inEdge) {VGA_R, VGA_G, VGA_B} = {8'h0, 8'h0, 8'h0}; // black
                if (inBall_1) {VGA_R, VGA_G, VGA_B} = {8'hff, 8'h66, 8'hff}; // pink
                if (inBall_2) {VGA_R, VGA_G, VGA_B} = {8'hFF, 8'h30, 8'h30}; // red
                if (inBall_3) {VGA_R, VGA_G, VGA_B} = {8'h56, 8'hca, 8'h32}; // green

                if (inBall_4) {VGA_R, VGA_G, VGA_B} = {8'h66, 8'h66, 8'hff}; // blue
                if (shelter) {VGA_R, VGA_G, VGA_B} = {8'h0, 8'h0, 8'h0}; // black
                end
            1'b1: begin
                if (insurface) {VGA_R, VGA_G, VGA_B} = {8'hff, 8'hff, gameover_counter[25:18]}; // white
                if (inEdge) {VGA_R, VGA_G, VGA_B} = {gameover_counter[25:18], gameover_counter[25:18], 8'h0}; // black
                if (inBall_1) {VGA_R, VGA_G, VGA_B} = {8'hff, gameover_counter[25:18], 8'hff}; // pink
                if (inBall_2) {VGA_R, VGA_G, VGA_B} = {gameover_counter[25:18], 8'hca, gameover_counter[25:18]}; // green
                if (inBall_3) {VGA_R, VGA_G, VGA_B} = {8'hff, 8'hdd, gameover_counter[25:18]}; // yellow
                if (inBall_4) {VGA_R, VGA_G, VGA_B} = {gameover_counter[25:18], gameover_counter[25:18], 8'hff}; // blue
                if (shelter) {VGA_R, VGA_G, VGA_B} = {8'h0, 8'h0, 8'h0}; // black
                end
            endcase
    end

endmodule
```