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FPGA Implementation of a Simple 3D Graphics Pipeline

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DOI: 10.15598/aeee.v13i1.1125

Abstract. *Conventional methods for computing 3D projects are nowadays usually implemented on standard or graphics processors. The performance of these devices is limited especially by the used architecture, which to some extent works in a sequential manner. In this article we describe a project which utilizes parallel computation for simple projection of a wireframe 3D model. The algorithm is optimized for a FPGA-based implementation. The design of the numerical logic is described in VHDL with the use of several basic IP cores used especially for computing trigonometric functions. The implemented algorithms allow smooth rotation of the model in two axes (azimuth and elevation) and a change of the viewing angle. Tests carried out on a FPGA Xilinx Spartan-6 development board have resulted in real-time rendering at over 5000 fps. In the conclusion of the article, we discuss additional possibilities for increasing the computational output in graphics applications via the use of HPC (High Performance Computing).*

Keywords

3D projection, FPGA, parallel processing, real time, VGA, VHDL.

1. Introduction

The drawing of graphics scenes in 3D obtained from their representations requires the processing of large volumes of data. Special chips are available for this purpose – GPUs which rely on mass parallelization. Under usual circumstances, CPUs are not suitable for these tasks (even though there do exist instruction sets supporting multiple computations), since by their design they process instructions serially and hence would require much larger frequencies to achieve comparable speeds. FPGA also support high parallelization and may be used to achieve high computational throughputs.

This project originated as a semester project with an initial goal of drawing 3D projections of simple wireframe models in real-time on a single chip, where the intent was to achieve very high values of fps. Since the described problem commonly lies beyond the boundaries of usual microcontrollers/CPUs, the solution has led to the creation of a hardware graphics pipeline for drawing on a screen via the VGA interface [1].

2. Graphics Pipeline

Current GPUs comprise many cores containing unified shaders, which allow the realization of operations previously carried out by vertex units, pixel units, TMUs (texture mapping units) and ROPs (render output units). Drawing of 3D models on the screen is basically the results of several consecutive blocks (simplified) [5]:

- Primitive processing – reading primitives, vertices and their connection.
- Vertex shader – the vertex shader transforms coordinates of vertices by their multiplication with the matrices of the scene. This is where the transformation from 3D $\rightarrow$ 2D occurs.
- Primitive assembly – vertices are joined into primitives.
- Rasterization – primitives are rasterized into pixels.
- Pixel shader – this is applied to each pixel of the rasterized scene and computes its color. This step also applies textures.

A vertex unit (whose functionality is nowadays included in the vertex shader) will suffice for the purposes of this work. The data source is a ROM with the vertices of the model, which is then transformed by the vertex unit to vertices in a plane. These vertices are then joined by line segments and drawn in video RAM, from which the VGA adapter will subsequently generate VGA signal for the screen.

The graphics pipeline consists of the unit carrying out the computation of the projection matrix (*GrxGenerateProjectionMatrix*) and the unit multiplying the projection matrix with the vertices of the displayed model (*GrxVertexProjection*). Both *GrxGenerateProjectionMatrix* and *GrxVertexProjection* together form the vertex unit and ensure the actual 3D → 2D display. The obtained 2D vertices are scaled to the required size and converted from decimal numbers represented with a fixed decimal point to integers into the monitor coordinates system and stored in the memory cache (the 2D vertex bank). Vertices from the cache are read by the unit drawing the wireframe model based on their connection map (from the ROM model). The model is drawn in the black-and-white video RAM (frame buffer), from which display data are read by the VGA adapter and displayed on the screen.

Displaying is ensured by the VGA adapter with binary modulation of base colors. The control of the whole *Cubido3D* project is ensured by one primary and several local FSMs (Finite State Machines). A simplified diagram of the graphics pipeline is provided in Fig. 1.

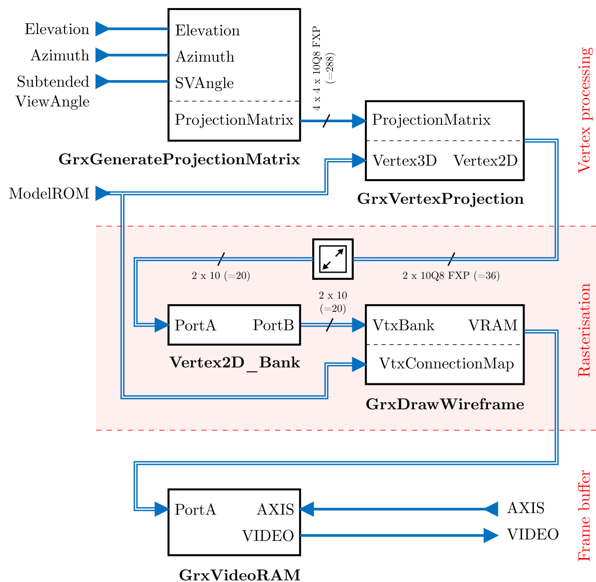

Fig. 1: Simplified diagram of the *Cubido3D* graphics pipeline.

Individual blocks of the graphics pipeline consist of separate VHDL modules or optimized IP cores which are a part of the Xilinx ISE development kit.

2.1. Perspective Projection

Displaying a 3D object in two dimensions is a linear transformation over the $\mathbb{R}^3$ vector space into $\mathbb{R}^2$. A special case of this is the projection transformation. This transformation can be described by the projection matrix. During projection, the dimension degrades from $\dim\mathbb{R}^3 = 3$ to $\dim\mathbb{R}^2 = 2$ and the vectors obtained by the transformation can be used to display the object on a plane (e.g. a screen). There exist two types of projection which are used in graphics: parallel projections (which include isometric, orthogonal, oblique projections etc.) and perspective projections. In this article we focus on the latter type of projections. Linear perspective projections always work with a representation of the beams from the projected object to the observer's eye (the camera) through a plane, on which the object is projected. See Fig. 2 for an illustration.

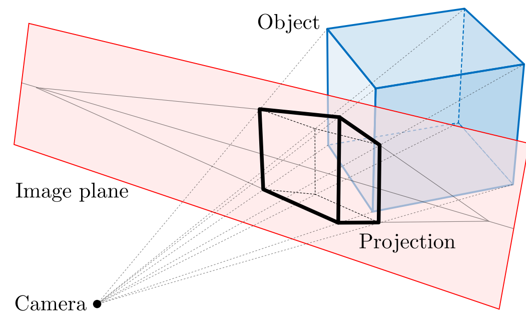

Fig. 2: Perspective projection of an object onto a plane.

The transformation matrix realizing perspective projection is obtained by multiplication of 3 matrices [4]:

$$\mathbf{A} = \mathbf{P} \cdot \mathbf{T} \cdot \mathbf{R}. \tag{1}$$

- The transformation matrix $\mathbf{R}$, which is obtained by a composition of rotation by axes x and z:

$$\mathbf{R_x} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(\theta_x) & -\sin(\theta_x) & 0 \\ 0 & \sin(\theta_x) & \cos(\theta_x) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \tag{2}$$

$$\mathbf{R_z} = \begin{bmatrix} \cos(\theta_z) & -\sin(\theta_z) & 0 & 0 \\ \sin(\theta_z) & \cos(\theta_z) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \tag{3}$$

$$\mathbf{R} = \mathbf{R_x} \cdot \mathbf{R_z}. \tag{4}$$

Rotation is typically entered in the form of an azimuth and elevation, where the following relations hold:

$$\theta_z = -\theta_{az},$$
$$\theta_x = \theta_{el} - \frac{\pi}{2}. \quad (5)$$

Figure 3 illustrates the effects of the transformation matrix.

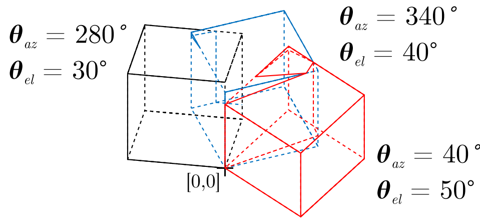

Fig. 3: Effects of the transformation matrix on the displayed object.

- The translation matrix $\mathbf{T}$ translated the starting point $[0, 0, 0]$ of the coordinate system of the object and has the shape:

$$\mathbf{T} = \begin{bmatrix} 0 & 0 & 0 & v_x \\ 0 & 1 & 0 & v_y \\ 0 & 0 & 1 & v_z \\ 0 & 0 & 0 & 1 \end{bmatrix}. \quad (6)$$

The translation moves the beginning of the coordinate system, usually to the center of the object. This forms the center based on which the object is rotated (Fig. 4).

$$\mathbf{v} = \frac{1}{2} + \frac{\sqrt{3}}{2} \cdot \begin{bmatrix} \cos(\theta_{el}) \cdot \sin(\theta_{az}) \\ -\cos(\theta_{el}) \cdot \cos(\theta_{az}) \\ \sin(\theta_{el}) \end{bmatrix}. \quad (7)$$

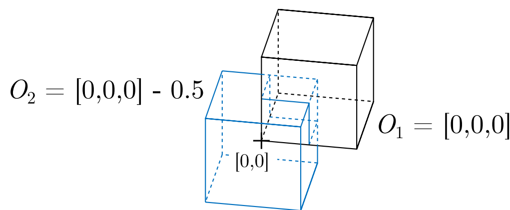

Fig. 4: Effects of the translation matrix on the displayed object.

If the coordinates of object vertices are set so that the object lies in $[0, 0, 0]$, the matrix becomes a unit matrix and the translation is not necessary.

- The perspective transformation $\mathbf{P}$ carries out the actual conversion from 3D → 2D and has the form:

$$\mathbf{P} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & -\frac{1}{f} & \frac{d}{f} \end{bmatrix}, \quad f = d, \quad (8)$$

where f is the focal distance, which can be computed from the viewing angle:

$$f = \frac{\sqrt{2}}{2 \cdot \tan(\frac{\phi}{2})}, \quad (9)$$

ϕ determines the rate of the projection deformation of the object. If $\phi = 0$, the projection degrades to an orthogonal projection.

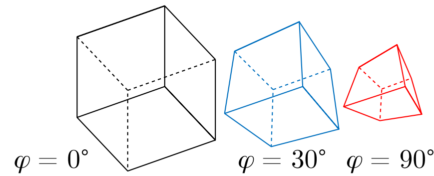

Fig. 5: Effect of viewing angle on perspective deformation of the display.

3. Implementation

The *Cubido3D* project implements a hardware-based graphics pipeline based on FPGA. Projection, translation of objects and generation of video signal is adapted for an architecture based on a programmable logic.

Aside from the graphics pipeline, the project also includes a VGA adapter generating the video signal for the screen, a memory of displayed models, blocks generating the background image + panel image and supporting logic (distribution of clock signal, control of the graphics pipeline etc.). Pipelining and strong parallelism are commonly used to obtain the target frequency of 100 MHz.

3.1. Cubido3D

Cubido3D forms the Top Level Module. It synchronizes input signals, controls the azimuths and elevation by counters with acceleration and the viewing angle by a counter with overflow protection. Combinations of buttons also allow the selection of the drawing model and the generation of a global reset.

The selected data of the model are, together with the azimuth, elevation and viewing angle, transferred to *GrxGraphicUnit*. *Cubido3D* connects the VGA adapter and FPs display on a 7-segmented display. Since FPGA doesn't have sufficient memory for double buffering, video RAM has a capacity of only 1 frame and must thus be redrawn synchronously at the time the screen is in an inactive area. Due to this, redrawing is always called during the receipt of the vertical synchronization impulse. Drawing is fast (takes approximately 200 μs in case of a cube) and thus finishes before the screen transfers to the active area.

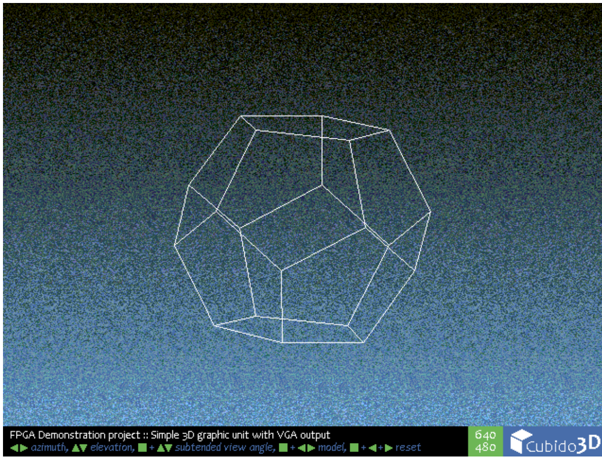

Fig. 6: Example of an output generated by FPGA captured on a VGA interface.

3.2. Implementation of the Graphics Pipeline

The graphics pipeline consists of the unit for computing the projection matrix, the vertex unit, the simple rendering unit and a two-port video memory.

The pipeline first deletes video RAM, computes the projection matrix with transferred parameters (azimuth, elevation, viewing angle) and reads the normalized 3D model from the vertex memory and their interconnections. This is then displayed in 2D and rescaled for display on the screen (numbers are converted with a certain offset and scale from FXP to integer form). The computer 2D vertices are stored into the small cache. The wireframe model is then drawn in the video memory from the computed 2D vertices.

1) Calculation of the Projection Matrix (*GrxGenerateProjectionMatrix*)

GrxGenerateProjectionMatrix is a unit which computes the matrix of a perspective display from received values of the azimuth, elevation and viewing angle (amount of perspective deformation). The computation of formulas Eq. (1) to Eq. (9) is adapted for processing via FPGA. The center of the projection (the target point) is fixed to the initial point of the coordinate system. Despite best efforts to make the computation as parallel as possible, it is strongly sequential and its processing is carried out by a state machine with 28 states. The computation of trigonometric functions is carried out by the CORDIC unit (*Cordic-Core_SINCOS* entity), which computes in parallel the sine and cosine functions for the entered angle. The computation of the tangent of the viewing angle is carried out in 2 steps: the first is the computation of the sine and cosine of the viewing angle, followed by their division. Division is carried out in an adjoined serial divisor. All additional computations are carried out by the *DSP48A1* unit which is part of the architecture of the used FPGA. *DSP48A1* is specifically configured to carry out the following computation:

$$R = A + (B - C) \cdot D. \tag{10}$$

The unit works with numbers with a fixed decimal (FXP) in the 10*Q*8 format. The computation is illustrated in the Fig. 7:

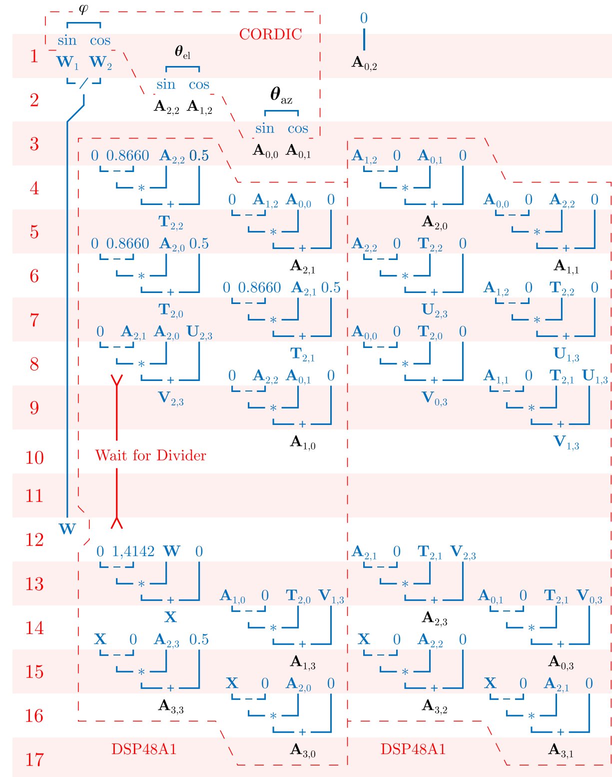

Fig. 7: Computation of the projection matrix by the *GrxGenerateProjectionMatrix* module.

The resulting projection matrix is serialized into a $4 \times 4 \times 10Q8$ bus, and thus has a width of 288 bits. The bus is connected to computational units via registers and bus multiplexes controlled by the state automaton.

The largest amount of running time is used by the serial divisors, and hence they are initiated shortly after the computation of the matrix begins and they work in parallel with the other computations.

2) Vertex Unit (*GrxVertexProjection*)

The vertex unit computes 2D vertices of the image by projecting their 3D template through multiplication with the projection matrix received from *GrxGenerateProjectionMatrix*. The whole principle is very similar to the computation carried out by the *GrxGenerateProjectionMatrix* unit. The computation is con-

trolled by a state machine (12 states) together with a divisor and 2 *DSP48A1*. Both *DSP48A1* realize the following computation:

$$R = A + B \cdot D. \quad (11)$$

The steps of the computation carried out by the vertex unit are illustrated in the Fig. 8:

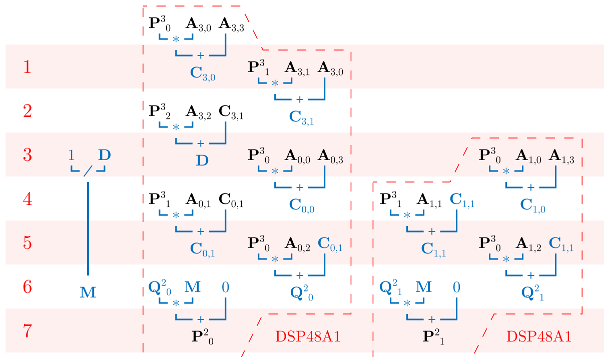

Fig. 8: Multiplication of the projection matrix and a vertex.

Since the computations of vertices are mutually independent, they can be carried out in parallel in several identical vertex units.

The coordinates for the templates of vertices are read from the model memory by the superordinate state machine in *GrxGraphicsUnit*. The obtained coordinates of vertices in the plane are first converted from FXP format to coordinates on the screen, or more specifically in the video memory, and stored in the memory cache (*Vertex2D_Bank*).

3) Wireframe Model Rendering (*GrxDrawWireframe*)

GrxDrawWireframe draws the wireframe from the 2D vertex bank (*Vertex2D_Bank*). The unit reads the connection map between individual vertices from the model memory into the wireframe model, and these vertices are then read from the bank of 2D vertices and transferred to *GrxDrawLine2D*, which draws a line segment between the vertices.

Memory control is managed by the unit's own resources.

4) Drawing a Line Segment (*GrxDrawLine2D*)

This unit draws a line segment defined by 2 integer 2D vertices into the memory. The vertices need not be ordered or otherwise preprocessing (the unit takes care of this automatically). The speed of generating points on the line is 1 point per 2 clocks. Generation

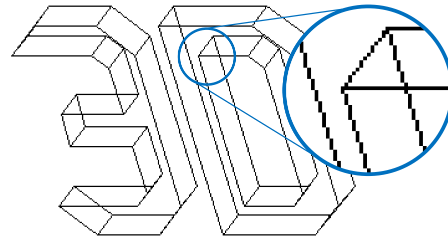

Fig. 9: One of the models stored in ModelDescriptionROM drawn directly by the graphics pipeline with a detailed view of the rasterization of the wireframe model.

and hence also writing can be stopped by a signal, and if necessary this can be setup by the state machine controlling video memory.

The state machine (12 states) first captures, compares and if necessary adjusts the order and coordinates of the input vertices (the unit transforms all line segments into the first half of the first quadrant – angular coefficient 0 to $\frac{\pi}{4}$). This is necessary to allow the generation of coordinate x by a counter; larger coefficients would lead to the loss of points on the line, see Fig. 10. It then computes their angular coefficient (the increase in the vertical axis per unit step on the horizontal axis). The number of the fractional (breakline) bits of the angular coefficient is set automatically so as to reach the target vertex. The unit then uses the counter to generate the horizontal coordinate and generates the vertical one by the accumulator. The vertical coordinate is rounded. Coordinates are also adjusted by the offset specified in point 1 and transformed back into their quadrant. Finally, the write signal is created.

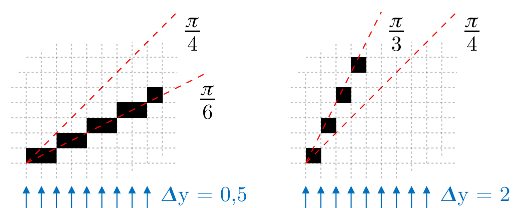

Fig. 10: Drawing of a line segment and the effect of the angular coefficient.

Generation of coordinates for a write request is carried out in 2 cycles, and the unit is hence capable of drawing 1 pixel per 2 cycles. In general the drawing process takes circa $40+2n$ cycles (where n is the number of drawn points). Interrupts of writing called by the video memory unit are not taken into account. Figure 9 illustrates the generation of a line segment.

5) Video Memory (*GrxVideoRAM*)

This module implements the video memory with a function for quick deletion of the whole RAM. Read-

ing and writing is realized by a state automaton, which works with a larger internal data bus than the required external one (and hence also a smaller internal address bus). This allows much quicker deletion of RAM. Part of the external address bus (the upper bits) addresses a location in RAM, whereas the lower bits map the external data bus to the greater internal data bus. Writing can in some cases take longer than 1 clock, since it is necessary to first read a data block in RAM, change the corresponding group of bits in this block via the input data for writing and then write this block, as illustrated in Fig. 11. The current block is cached.

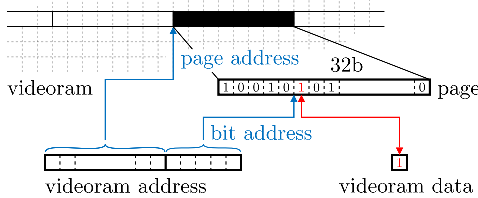

Fig. 11: Video memory architecture.

3.3. VGA Adapter (*GrxAdapterVGA*)

A generic VGA adapter which supports various resolutions and color depths based on the configuration of [6]. Its correct operation is based on an incoming signal with a VGA pixel frequency from the main clock distribution through the *DCM* (Digital Clock Manager) module.

Clock domains are strictly separated. All simple signals are resynchronized by the *GResynchronizer* block (part of the library of general project components) and the transmission of video signal from the input clock domain is resolved via a FIFO queue with separated clocks for reading and writing. This queue is also used as a line cache (writing is carried out on a line-by-line basis). The queue is inserted as an IP core to ensure timing and synchronization. Synchronization of writing in the line cache is carried out via the *LineStrobe* (beginning of a line) and FrameStrobe (beginning of a frame) signals in combination with the PixelRequestAxis (current coordinate for writing) signal.

3.4. Project-Oriented Modules

The source files of the project connect individual components into larger wholes – they connect the memories, the graphics pipeline, and the VGA adapter and also take care of synchronization, adjustment and processing of input and output signals.

1) Model Memory (*ModelDescriptionROM*)

The definition of models consists of a list of vertices (*Vertex3DBankROM*) and their connections (*VertexPointerROM*). Models are stored sequentially. *ModelsDescriptorROM* is used to store the offset to *Vertex3DBankROM* and *VertexPointerROM*, where the model begins and simultaneously the length of the records of the model in these memories. *VertexPointerROM* consists of a map of vertex connections – it contains tuples of indices (addresses) into *Vertex3DBankROM* which define a line segment in the wireframe model. Figure 12 illustrates the model memory architecture.

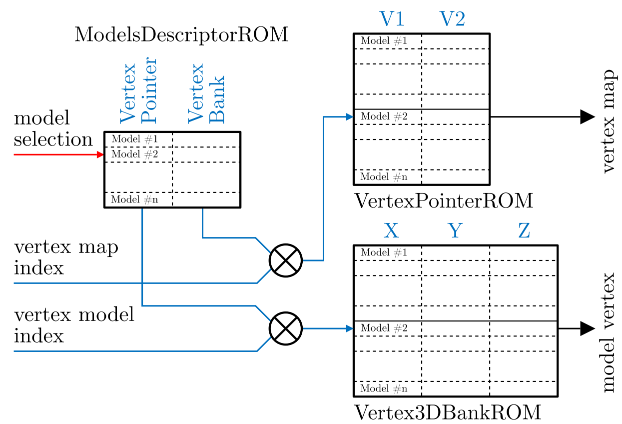

Fig. 12: Model memory architecture.

2) Background Video Signal Generator (*BackgroundVisualizer*)

This takes care of the generation of RGB signals for drawing the background in VGA. It draws a vertical color shift from black.

$\theta_{az} = 0, \ \theta_{el} = 0$

$\theta_{az} = 0, \ \theta_{el} = \pi$

$\theta_{az} = \pi, \ \theta_{el} = 0$

$\theta_{az} = \pi, \ \theta_{el} = \pi$

Fig. 13: Examples of generated background for various azimuths and elevation (rotated by 90°).

The hue is based on the azimuth and elevation and hence changes depending on the "rotation" of the object. The formula used for the video signal v is:

$$\mathbf{v}_{color} = y \cdot \left(\frac{2+ \begin{bmatrix} -\cos(\theta_{az}) - \cos(\theta_{el}) \\ \cos(\theta_{az}) - \frac{\cos(\theta_{el})}{2} \\ \cos(\theta_{el}) - \frac{\cos(\theta_{az})}{2} \end{bmatrix}}{2048} + \right. \\ \left. + \frac{\text{rand()}}{4} \right). \tag{12}$$

The computation of goniometric functions is carried out by a separate CORDIC core with its own controller, which periodically sends the azimuth and elevation to the core and then writes these in the registers. The computation is then a simple connection of adders and multipliers with suitable pipelining.

Since an 8-bit color depth is insufficient for drawing a color shift, the dithering technique is used through the simple generation of noise generated by the *GRandGeneratorLFSR* block.

3) Panel Image (*PanelImageROM*)

This ROM stores the panel image drawn on the screen (Fig. 14). The image has a resolution of 640×32 with a 2-bit color depth. The colors on the image are indexed.

Fig. 14: One of the images stored in *PanelImageROM*.

Image data are stored in the ROM organized as $(640\times32)\times2$ bits. The address is this computed from coordinates and the data output is 2-bit – i.e. 4 indexed colors in total. The output of the previous ROM is sent to the look-up table which converts the index to a specific color with a 256 color depth. Figure 15 illustrates the realization of the memory.

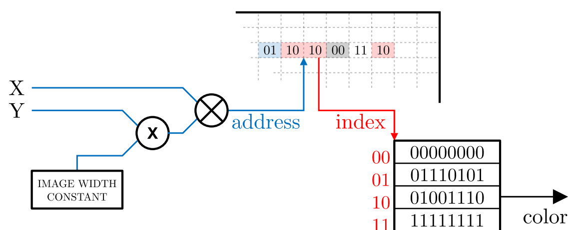

Fig. 15: Storage of the panel image.

3.5. The *Libgenerics* Library

This library provides the basic functional blocks and functions:

- *GResynchronizer* – Resynchronizer of one-bit asynchronous signals into the internal clock domain.
- *GResetSynchronizer* – Resynchronizer of reset into the internal clock domain.
- *GDebounceFilter* – Debouncing filter for button press.
- *GEdgeDetector* – Detector of rising/falling/both edges of the monitored signal.
- *GAccumulator* – Accumulator register with synchronous reset and overflow detection.
- *GRandGeneratorLFSR* – Linear shift feedback register (LSFR) implementing a general pseudorandom number generator. This is requires primarily for the creation of a smooth color shift in the drawn background.
- *GNonOverflowCounter* – A non-overflowing bidirectional synchronous counter with synchronous reset and pre-divisor. This is used to set the viewing angle.
- *GAccelerateCounter* – Bidirectional binary counter with customizable TOP value and synchronous reset. The counter freely overflows in both directions, has a configurable counter acceleration speed and a pre-divisor of the clock signal. This is used to set the azimuth and elevation and creates the effect of "gradual" rotation of the object on the screen.
- *GBcdCounter* – Generic BCD increasing counter with synchronous reset.
- *GBcd7Display* – BCD display driver consisting of 7 segmented digits. Forms the FPS indicator together with *GBcdCounter*.
- *GBlockRAM* – 2-port block RAM with a single clock signal.
- *GSerialDivider* – Unsigned generic serial divisor. Designed based on the application note [2]. The computation takes approximately $2n+2$ clock cycles (where n is the bus width), which allows for future improvement.

4. Future Work

Parallel processing may under certain conditions be used to improve the efficiency of the 3D functions. However, it needs to be said that this method is only suitable for algorithms which can be efficiently parallelized. In this case it is possible to use a large number of FPGA circuits which are interconnected via appropriate data channels. Currently, there exists a number of commercially available HPC (High-Performance Computing) systems ranging from dozens to thousands of FPGA circuits. These computational units may significantly speed up the computations in various areas, such as medical imaging, cryptography, statistical data processing, biological sciences etc.

Efficient HPC systems usually place FPGAs in individual cards inserted into slots of the motherboard with high data throughput. Communication between the user and FPGA cards is secured by the host computer via the corresponding API interface.

The Rivyera HPC (SciEngines GmbH) system with Xilinx FPGA circuits was selected for the further development of the project. The efficient use of such a HPC system is based especially on the design of a suitable design of the logical structure for FPGA circuits and the programming of applications for data exchange between the user and the FPGA logic. The digit design for FPGA based on VHDL can be created through the Xilinx ISE development kit. The programming of application software on the host PC is then possible through the API for C and Java.

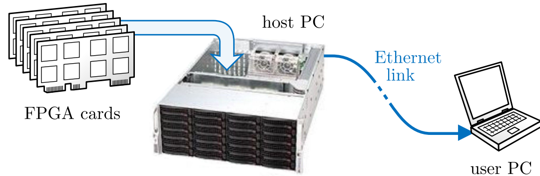

Fig. 16: Overview of a Rivyera HPC with FPGA circuits.

Rivyera HPC offers a highly efficient bus system which allows the organization of FPGA circuits into a systolic chain, which minimizes delays in the system caused by connections.

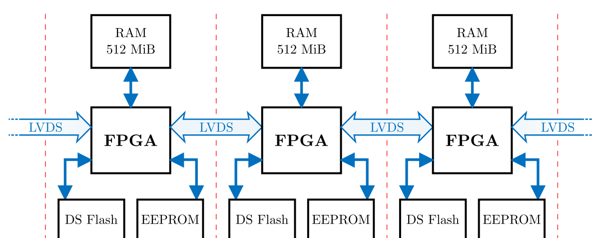

Fig. 17: Linear systolic chain based on FPGA [8].

Individual Rivyera cards are equipped with massive FPGA circuits of the S6-LX150 line. Each user FPGA circuit on the card is connected to a memory subsystem consisting of up to 512 MiB DDR3 RAM, 256 kiB of EEPROM memory and a micro SD/HC Flash (selected). Data transmission between individual FPGA circuits will be carried out through the bus architecture and connection diagrams implemented in the sophisticated API.

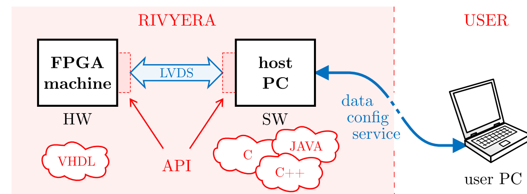

Fig. 18: HW and SW computing methods in Rivyera HPC.

Assuming the efficient use of connections and optimal digit design, we can reach a data throughput between adjacent FPGAs of up to 2 $\mathrm{Gb \cdot s^{-1}}$. However, the actually usable throughput may differ based on API and FPGA limitations [8] An efficient systolic chain can be used between FPGA circuits on a single card as well as between individual cards in the system. The Rivyera can be equipped with up to 128 FPGA circuits (or up to 256 FPGA circuits by doubling the number of cards).

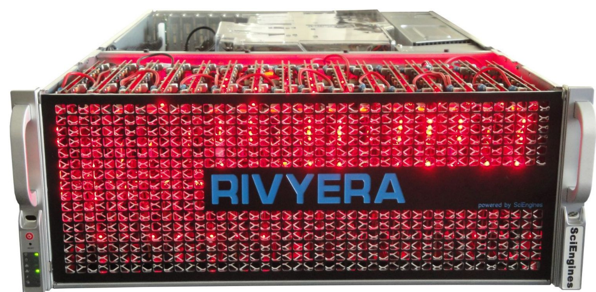

Fig. 19: RIVYERA supercomputer with 256 FPGAs [8].

5. Conclusion

The implementation of the project is intended for the Xilinx Spartan-6 circuit with a graphics output to VGA, e.g. [3]. The procedures and outputs of the project are useful in many built-in control systems which are based on FPGA circuits. The most interesting applications will probably be found in technical equipment which relies on virtualization and real-time computations. One of the areas where highly efficient computations and parallelism are both required is medical data imaging. Another advantage of this hardware-based solution is that it increases functional

safety, which is a difficult task in the case of sequential tools based on microprocessors. Similar methods have been used in areas such as mobile applications and even home care systems, see [7]. Techniques for design verification form an important part of the design methods for these programmable circuits. These provide us with near-certainty regarding the actual reliability of the programmable logical circuits.

Tab. 1: FPGA device utilization summary.

Number of FSMs	12
Number of Block RAMs	32 of 32 (100 %)
Number of Slice LUTs	4237 of 9112 (46 %)
Number of bonded IOBs	28 of 232 (12 %)
Number of BUFG/BUFCTRLs	3 of 16 (18 %)
Number of DSP48A1s	10 of 32 (31 %)
Number of PLL_ADVs	1 of 2 (50 %)

Acknowledgment

This paper has been elaborated in the framework of the project "Support research and development in the Moravian-Silesian Region 2013 DT 1 - International research teams" (RRC/05/2013). Financed from the budget of the Moravian-Silesian Region. The work and the contributions were supported by the project SP2014/194 "Biomedicinske inzenyrske systemy X".

References

[1] KASIK, V., A. KURECKA and P. POSPECH. 3D Graphics Processing Unit with VGA Output. *IEE Proceedings - Circuits, Devices and Systems.* 2005, vol. 152, iss. 3, pp. 388–393. ISSN 1474-6670. DOI: 10.3182/20130925-3-CZ-3023.00081.

[2] AVR200. *Multiply and Divide Routines.* Atmel, 2009. Available at: `http://www.atmel.com/Images/doc0936.pdf`.

[3] Nexys3. *Board Reference Manual.* Digilent, 2013. Available at: `http://www.digilentinc.com/Data/Products/NEXYS3/Nexys3_rm.pdf`.

[4] BENSAALI, F., A. AMIRA and A. BOURIDANE. Accelerating matrix product on reconfigurable hardware for image processing applications. *IEE Proceedings - Circuits, Devices and Systems.* 2005, vol. 152, iss. 3, pp. 236–246. ISSN 1350-2409. DOI: 10.1049/ip-cds:20040838.

[5] HO AHN, S. *OpenGL programming tutorials, examples and notes written with C++* [online]. 2013. Available at: `http://www.songho.ca/opengl/index.html`.

[6] TRAN, V.-H. and X.-T. TRAN. An efficient architecture design for VGA monitor controller. In: *2011 International Conference on Consumer Electronics, Communications and Networks (CECNet).* XianNing: IEEE, 2011, pp. 3917–3921. ISBN 978-1-61284-458-9. DOI: 10.1109/CECNET.2011.5768261.

[7] PENHAKER, M., M. STANKUS, J. KIJONKA and P. GRYGAREK. Design and Application of Mobile Embedded Systems for Home Care Applications. In: *2010 Second International Conference on Computer Engineering and Applications.* Bali Island: IEEE, 2010, pp. 412–416. ISBN 978-1-4244-6079-3. DOI: 10.1109/ICCEA.2010.86.

[8] SciEngines GmbH. 2014. Available at: `http://www.sciengines.com`.

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