

Geometrical Picture Integration in SEMI-CAVE Virtual Reality

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Abstract: Virtual reality (VR) is the most fascinating multimedia solution of recent years. Cave (Cave Automatic Virtual Environment) is the most advanced example of VR installation. The aim of the work is to present an image stitching problem in specific cave installation. The low-budget installation called SEMI-CAVE has been built to study the impact of visual environment on human psychophysiology at the workplace. Six projectors display images on four walls of a relatively large room. Correct stitching of images with perfect geometry is the deciding factor in ensuring good immersion in VR under these conditions. We have developed a special image stitching subsystem working in the SEMI-CAVE solution. The subsystem makes it possible to easily combine individual images to ensure the correct geometry of the displayed content. In addition, the implementation of the stitching subsystem was carried out at the shader level, which ensured the fastest possible technical solution. The work presents subsystem assumptions, the method of implementation and conducted tests.

1 INTRODUCTION

1.1 Motivation

Virtual reality (VR) is one of the most attractive computer science solutions in recent years. Attractive not only for players of computer game and advertising specialists, but also scientists from many fields. Cave (Cave Automatic Virtual Environment) is the most spectacular example of VR installation. Cave is a solution known for many years, but due to the costs and many technical problems this solution is relatively rarely used.

The realization discussed here – SEMI-CAVE – is an example of cave implementation, projected and developed in recent years in the Central Institute for Labour Protection - National Research Institute (CIOP-PIB). It is one of the laboratories which were built as a part of Tech-Safe-Bio project (TECH-SAFE-BIO, 2015). The research plans related to the SEMI-CAVE laboratory include interdisciplinary study on health and safety of employees. VR solutions will allow the researchers to study the impact of physical environment on workers. The laboratory was initially launched in the end of 2015. After the first work (technical issues and calibration)

we focused on experiments with acquiring images for preparing VR environment. The impressions of viewers have confirmed the correctness of the project concept – i.e. sufficient immersion into VR.

The quality of the displayed image in CAVE installations, is a key issue determining the correctness of immersion into the virtual reality created inside the installation. Most often, two aspects of this problem are discussed (Slater, 2003):

- **Immersion Into The Virtual Environment.** This concept defines how well VR represents the real world. We can list the following parameters: correctness of stitching and image geometry, color rendering and perception, viewing angle, image resolution, etc.;
- **Presence.** An aspect relating to the perception of virtual reality by the user. In practice, not measurable, connected with the person using the installations at a given moment. This parameter depends on: the content presented for a long time inside the installation and the emotional state. It depends on the quality of the immersion in VR.

The first thing SEMI-CAVE users see when entering a room is of course the whole image displayed on all four walls. The impression of

immersion is determined at this point by the correctness of building virtual reality through component images (displayed on individual walls). The decisive influence is the quality of stitching the images and maintaining the correct image geometry throughout the entire installation.

1.2 The Aim of the Article

The main aim of this paper is to present the stitching subsystem in the SEMI-CAVE laboratory. The geometrical integration of the images is one of the most important tasks in preparation of the VR installation environment. The proposed and tested tools in SEMI-CAVE allow for correcting geometry of the displayed images regardless of the projector settings, always in the same, easy way.

2 THE STITCHING PROBLEM IN CAVE INSTALLATION

The most advanced VR installation called CAVE (Cave Automated Virtual Environment) was introduced in 1991 (Cruz-Neira et al., 1992). Using this idea, several different solutions (CAVE2, wall of monitors) were created later (Kim et al., 2013). There are also many publications on the technical aspects of CAVE solutions. The review works deserve special attention (Zhou et al., 2009, Kim et al., 2013, Muhanna, 2015).

The problem of stitching images in CAVE installations involves two independent issues; both are essential for our SEMI-CAVE laboratory:

- display stitching, and thus stitching to correct the properties of display devices. Aspects such as changes and inaccuracies in projectors position, changes and differences in displaying information are taken into account;
- panorama stitching, thus stitching the images prepared for display in the CAVE installation. In our laboratory also, the previously prepared fragments must be combined into a single unit, which enables proper display in the entire SEMI-CAVE installation (on all walls).

2.1 Display Stitching

In an ideal (theoretical) situation, the projector should be set so that the image it generates is perfectly rectangular (undistorted). At the same time, the image generated by this projector is adjacent to the second image in such a way that

together they form a coherent image with an unnoticeable boundary (connection). Of course, this situation should occur for each pair of neighboring images and the projectors that generate them. In practice, it is not possible to achieve such an ideal situation. Additionally, all parameters of device (including optical) change (degrade) over time. The only way to solve this problem is to use software that corrects the image geometry. The software should meet the following requirements:

- the possibility of geometry correction on the principle of converting a quadrilateral into a quadrilateral with the determination of appropriate colors inside the resultant quadrilateral by interpolation;
- software support implemented by means of a simple, intuitive interface enabling easy shape correction;
- the ability to visually check the correctness of the proposed geometry correction by using (or comparing with) a well-recognized pattern;
- two software operating modes: standard mode (when displaying images) and editing mode, during which geometry and color can be corrected. It can be assumed that the editing mode (correction) will be used relatively rarely (once a month or less frequently);
- the correction mode of the software should, above all, meet one basic condition. It must work all the time while displaying each image in the SEMI-CAVE installation. The implementation of this task should be done in the most effective way, using the computer resources as little as possible.

2.2 Panorama Stitching

Currently, several algorithms are used to combine images. The most popular methods based on feature extraction are the SIFT and SURF algorithms. SIFT (Scale Invariant Feature Transform) was proposed by David Lowe in 1999 (Lowe, 2004). Initially, it only included the problem of detecting the object, that was sought in the photo. It was quickly extended to stitch fragments (Evans, 2009) and to the creation of panoramas (Hess, 2010). The SURF (Speeded Up Robust Features) algorithm was developed by Herbert Bay in 2006 (Bay et al., 2008). It is used to detect and describe images based on characteristic points (Evans, 2009, Hess, 2010). The SURF algorithm is partially based on SIFT, but is estimated to be several times faster in its standard form than the SIFT. (Schweiger et al., 2009).

2.3 Quadrilateral into Quadrilateral Transformation

Let points $T_0T_1T_2T_3$ define quadrilateral. We are looking for a transformation Ψ , which allows for converting quadrilateral $T_0T_1T_2T_3$ into quadrilateral $P_0P_1P_2P_3$ assuming the appropriateness of vertices. Vertex T_i is converted to vertex P_i (Figure 1).

Conversion of a quadrilateral into a quadrilateral is a geometric problem occurring in computer graphics (Heckbert, 1989), image processing (Bahram, 2002) and machine vision (Davies, 2005).

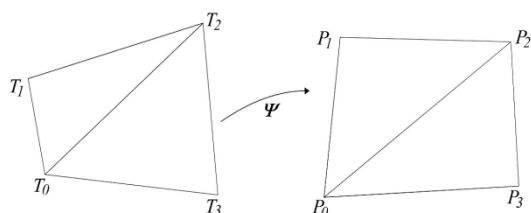


Figure 1: Transformation of the quadrilateral $T_0T_1T_2T_3$ into the quadrilateral $P_0P_1P_2P_3$.

From a formal point of view, the transformation of a quadrilateral into a quadrilateral is described by homographic functions. This issue we can find in many books related to image processing. The simplest solution to this problem is to propose an algorithm that uses a bilinear transformation. Comparative analysis of various solutions of this problem (Augustynowicz and Sawicki, 2016) shows that it is difficult to indicate one universal algorithm that would always carry out the task in the most effective way. In specific conditions of a particular application, it is worth considering the choice of method. Nevertheless, in contemporary textbooks (Hartley and Zisserman, 2004), the authors recommend the DLT (Direct Linear Transformation) algorithm (Abdel-Aziz and Karara, 1971) as the best, practically universal solution. At the same time, the DLT method is often cited in the literature as the basic method for camera calibration in the implementation of projection (Bardsley and Li, 2007, Dubrofsky, 2009).

3 SEMI-CAVE LABORATORY

Our installation (SEMI-CAVE) was dedicated to study the impact of visual environment of the workplace on human psychophysiology. The VR installation and the virtual environment created in this way should allow different working tasks to be performed in a proper – specific environment. This

way the most important argument for choosing the type of VR installation was the need for relatively large room dimensions (VR space). We have assumed that our virtual reality will be realized in a room of dimensions: 8.6m x 4.3m with internal projection. The minimum height of the image on the wall is 2.8m and there are no images on the floor and the ceiling. Such assumptions provide a practical compromise between the simulations of the working environment and the immersion benefits of the virtual environment. Details of SEMI-CAVE technical aspects were presented in (Sawicki et al., 2017).

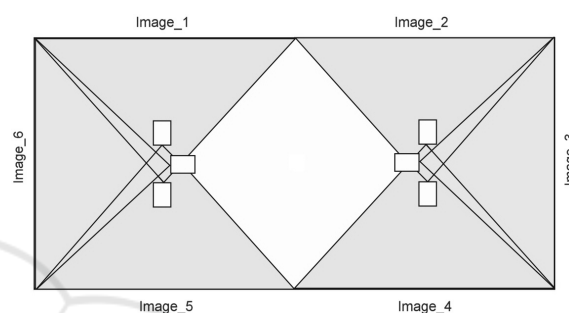


Figure 2: Arrangement of projectors that create six images on the four walls.

We used six projectors for displaying images (Figure 2). The main parameters are: brightness at the level of 4000 lm ANSI, WUXGA resolution (1920x1200), LCOS matrix, short throw optics with Lens Shift and Keystone Correction in two directions. These parameters make it possible to obtain the expected shadow-free work area. The projector has a built-in edge blending mechanism which allows for basic stitching of the images. This mechanism was used in the initial stage of the installation. Initial, precise settings of projectors and their hardware calibration ensured the correct display and stitch of images. However, growing mismatches have been observed over time. They mainly result from vibrations and aging of the supporting structure on which the projectors are mounted. The problem turned out to be so important that a few months after installation, there are significant deviations between the images displayed by individual projectors. This has an important impact on the perception of images, and thus on immersing into VR. Using the installation for a year has shown that from time to time a correction of the image stitching is required.

The standard operating scheme in our laboratory, as in CAVE installations, allows for separating the work of visualization algorithms into stages. On the

other hand, stitching the panorama in the SEMI-CAVE installation is a rather rare task, although it is necessary to combine real images with VR. It is advisable to use known and available software packages that allow for professional combination of panoramas. A well-known analysis of the available software (Comparison, 2018) has been published and shows that Hugin program is currently one of the most effective programs using feature extraction methods (Hugin, 2018). This program uses the PanoTools library (PanoTools, 2013) and is free software distributed under the GNU GPL. An additional advantage is that it is a software that allows you to use a very wide set of different projections – in particular: rectilinear, cylindrical, spherical, and many others such as Mercator and sinusoidal projections. This advantage was decisive when choosing a solution – the proper projection in CAVE installations has a decisive impact on the immersion in the virtual world.

The camera calibration is compatible with the calibration of projectors in the SEMI-CAVE installation. Analyzing these known solutions, we assumed that the DLT method is practically the best solution to the problem of quadrilateral to quadrilateral conversion for the SEMI-CAVE installations. On the other hand, in our software the algorithm of transformation will be used in two situations: as a standard driver at the shader level and as one of many applications for preparing images of real objects to be used in SEMI-CAVE.

4 PROPOSED METHOD OF CORRECTION FOR DISPLAY STITCHING

In a small room of a typical CAVE installation (e.g. 2m x 2m x 2m), the VR space in relation to the real space can be set practically arbitrarily. Even slight deviations from the vertical should not be noticeable. It is enough to match the quadrilateral images between each other to stitch the images. In SEMI-CAVE we deal with relatively large real space and stitching operation is not so simple. The basic problem is the need to define the reference level of the VR space and match it to the selected reference level of the real space. Theoretically, this is the adjustment of the horizon, but in practice "horizon" may mean a certain pre-arranged reference level relevant (and important) to the given content of the displayed image.

We assumed that the horizon line can be independently defined for each image. This means that it can be placed in any image height defined independently (Figure 3). This approach gives the possibility to define a common horizon line for all six displayed areas in a convenient way. The horizon understood in this way becomes the reference line for the displayed information in the entire SEMI-CAVE installation. It is worth emphasizing that in such a situation it is possible to determine the horizon line in the displayed areas, and then compare this line (and its possible correction) with the line pattern obtained from the laser level set in the SEMI-CAVE laboratory. This allows eliminating cases where the images are properly stitched together, but the entire set of images is distorted. It should be remembered that in a large spaces, VR and real, it is very difficult to control distortion of global geometry when the user corrects local stitching. The horizon line as a reference level in the whole space (laboratory) makes this correction task much easier.

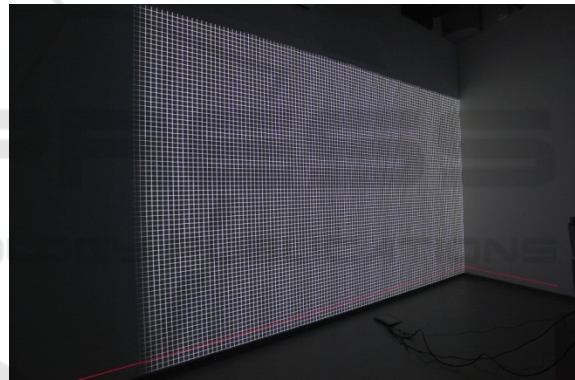


Figure 3: The position of the horizon line (red) arbitrary defined at the bottom of images.

At the software level each of the six displayed images functions independently and is displayed independently. The configuration of each display is also implemented independently. This approach to display gives the possibility of individual geometry settings, and thus gives the opportunity to correct individual geometry for each of the projectors.

In the management of the display at the graphic card level, we have adopted a normalized area defining the geometry of the displayed image. It is defined by the square $\{(-1,-1), (1,-1), (1,1), (-1,1)\}$. After the first selection of the position of the horizon line (y_{hor} selection), this area will be split into two rectangles:

upper $\{(-1,y_{hor}), (1,y_{hor}), (1,1), (-1,1)\}$
 lower $\{(-1,-1), (1,-1), (1,y_{hor}), (-1,y_{hor})\}$.

This allows for independent correction of both rectangles. In this case, the operator can change the position of six points. However, for the four vertices of the normalized square it can change both x and y coordinates, while for the two vertices associated with the horizon line, only x coordinates (y coordinates for this line were set at the horizon definition level).

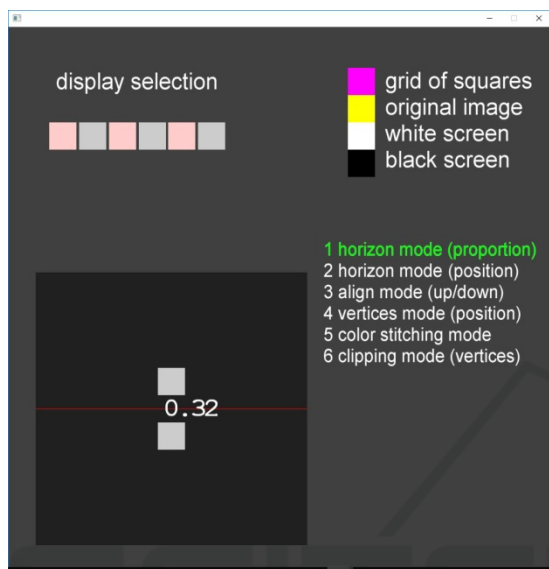


Figure 4: The GUI control panel of the software for stitching display in editing mode. The step of changing horizontal line position is selected (horizon mode). There is a possibility to change position of the horizontal line with the mouse or by entering a number that is the proportion of the position relative to the height.

The software for stitching the display in the editing mode gives the possibility to modify the position of the respective elements in several steps. In the first step, the operator selects the position of the horizon using the GUI (Figure 4). Operator has two possibilities of changing the position: by the value of proportion (y position of the horizon line in relation to the high of whole screen) or by the position movement (by mouse). In the next step there is possibility to align the VR horizon to real horizon. It can be done by moving the whole image up or down. In this step laser level is required as a special additional equipment. In the third step (vertices mode), the operator can intuitively reposition the selected vertex using mouse movements. (Figure 5). This approach gives very wide possibilities to change the shape of the area to ensure the adaptation to practically any conditions of physical display by projectors. And it is implemented in a simple and intuitive way. On the

other hand, the horizon line provides a reference level that is not ensured by changing only the position of vertices.

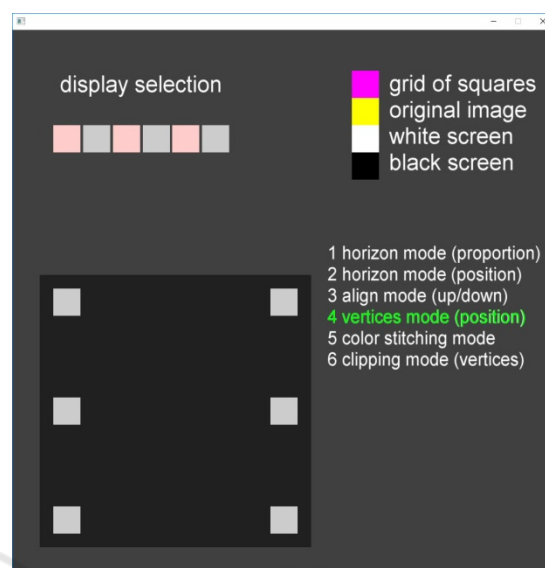


Figure 5: The GUI control panel of the software for stitching display in editing mode. The step of changing vertices position is selected (vertices mode). Position of each can be changed independently with the mouse.

In addition, in the last step (clipping mode) the operator can define the position of clipping lines in order to clip the image to the standardized area. In this mode only the position of the main vertices (without horizon vertices) is taken into account (Figure 6). Using this operation, the edges of neighboring images can be independently aligned (on a common wall or in the corners of the room).

The full algorithm for geometry correction in SEMI-CAVE is as follows:

1. define the horizon level for the entire VR space;
2. for each image: define the appropriate horizon line (according to VR horizon level);
3. display the level of the (real) horizon by using the laser level in the position closest to the displayed horizon lines from the VR space;
4. for each image: adjust the image position to match the horizon of the VR space to the horizon of the real space;
5. for each image: adjust the position of the vertices, according to stitch images in pairs (pairs that are adjacent);
6. for each image: define clipping line for the image, according to pairs of images (pairs that are adjacent).

The image stitching subsystem has been implemented at the shader level for the graphics card processor. The software has been prepared in the Visual Studio environment. For operating graphics in the working mode, the Vulkan environment was used (Sellers and Kessenich, 2016, Overvoorde, 2017). This is the most modern and probably the most interesting technology currently used to program advanced graphics. In the edit mode, OpenGL environment was used. All implemented operations within the appropriate shader have hardware representations in the graphics card processor. On the other hand, the division into appropriate procedures in OpenGL and Vulkan was designed to achieve the maximum performance of a given processor. Moreover, since Vulkan is a continuation of OpenGL and both libraries were designed by the same company, most of the procedures in them can easily be used interchangeably. This has been effectively applied in the SEMI-CAVE software.

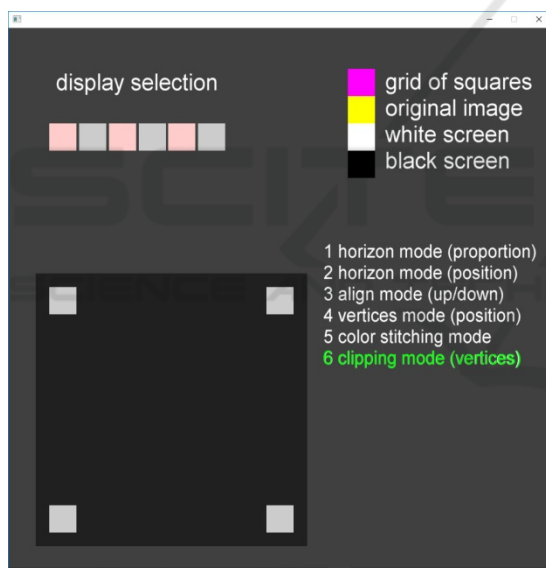


Figure 6: The GUI control panel of the software for stitching display in editing mode. The clipping mode is selected. Position of four vertices can be change independently with the mouse.

5 VERIFICATION OF THE SOLUTION

As part of the initial software tests, the correctness of the implementation of individual operations was checked and the work of algorithms for different ranges of geometric correction was analyzed. Next, we carried out the geometry correction in real

conditions in the SEMI-CAVE laboratory. Verification of the proposed solution should be related to the evaluation of the stitching correctness and appropriate usability tests. However, in our conditions it is very difficult. The images are either properly stitched or not – it is difficult to analyze intermediate states. Therefore, we have proposed a simple metric that gives the answer whether the correction is done well. The control images (grid pattern) are designed in such a way that the positioning of the corresponding control points can be determined with accuracy to a single pixel. On the one hand, such accuracy is sufficient to assess the correctness of stitched images; on the other hand, practically no better resolution is possible.

The first step in testing the developed software for geometric correction was to stitch different component images, including combining images in the area of display on one (common) wall with two projectors and in the corners of the room where the adjacent images were displayed on adjacent walls. We have developed control images using the black and white grid of squares displayed in the positive or negative version. They were chosen for the testing and correcting the images geometry. The control images facilitated the work greatly.

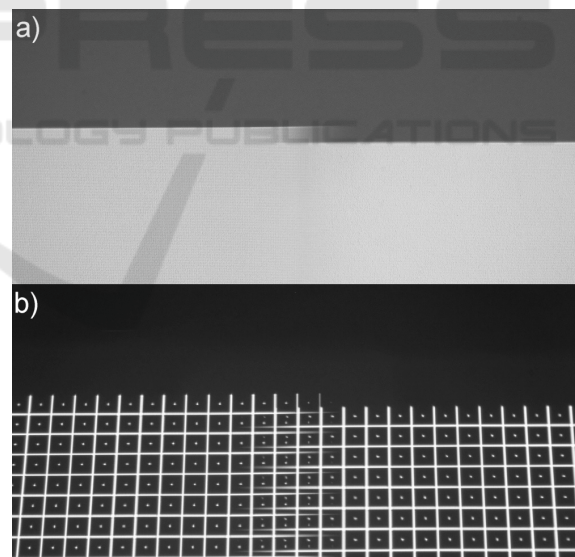


Figure 7: Area where two component images from different projectors are displayed. a) The white rectangles are displayed. b) The grid squares are displayed as control images. Visible shift of images.

The final tests were done in SEMI-CAVE, in the real arrangement of projectors, the positions of which had not been adjusted. The aim of these tests was to adjust and correct the real geometry. These tests were carried out after about a year after the

projectors' hardware was set up (calibrated) of. Such a long working time caused that the influence of vibrations and aging of the mechanical elements of the construction impacted the changes in the position of projectors. Figure 7 shows a picture of an example area in which two images from neighboring projectors are displayed per wall. Visible, clear shifting of the images reaches a size of approximately 2 cm.

The consequences of decalibrating the position of projectors are visible on the example images of the Warsaw Saski Garden displayed in SEMI-CAVE. Figure 8 shows a fragment with a clearly visible divergence of component images. Figure 9 shows an enlarged fragment of images of the Warsaw Saski Garden with clearly visible improved display geometry. This is a fragment of the area shown in Figure 8.



Figure 8: Area where two component images from different projectors are displayed. The consequence of shift of images presented in Figure 7.



Figure 9: An enlarged part from area shown in Figure 7 after correction. We can see the correct (uniform) border between the lawn and the path.

It is worth noting that the possibility of displaying images in the SEMI-CAVE installation is possible only after closing the editing mode of the

stitching subsystem. This means that the correction software sets the correction rules in the editing mode, and the rules are applied at any time during the software operation (in the display mode) and are valid until the next change in the editing mode. Thus the view, the fragment of which is shown in Figure 9, can be displayed after the correction in stitching mode and then after closing this mode.

Similar examples of corrections have been made many times in the SEMI-CAVE installation for different display areas. All experiments were successful – just like the views presented in the article. The correctness of the conducted tests confirms the correctness of the introduced solution concept, as well as the correctness of the software implementation.

6 SUMMARY

In the article, we described the problems of stitching images in a complex CAVE installation. We have proposed the method to solve the problem and developed the proper stitching subsystem. The subsystem allows for combining individual images to ensure the correct geometry in the displayed space. In addition, our stitching subsystem gives full control over the image creation process, which is an important advantage of our own solution.

The relative large size of the real space in SEMI-CAVE required a different, more advanced stitching approach than used in typical CAVE applications. A good solution facilitating the work was the horizon line with the possibility of arbitrarily setting its level. The experience and methods of stitching images in the panorama were also very helpful.

The image stitching subsystem has been implemented at the shader level and it is directly executed by the graphics card processor. This guarantees low CPU load of the main computer by the whole task of geometric correction. The software has been prepared using Vulkan – the best contemporary technology for advanced graphics programming.

We have conducted a series of tests in the real conditions of the SEMI-CAVE laboratory. The tests confirmed the correctness of the proposed solutions. The interface for setting correction parameters in the form of appropriately prepared GUI proved to be very convenient in use. The best confirmation of the stitching subsystem operation is the good impression of immersion into VR after the geometry correction.

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