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To cite this article: V Alekseev et al 2019 J. Phys.: Conf. Ser. 1278 012032

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Simulation images of external objects in a virtual simulator for training human-machine systems operators

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Abstract: The article presents the results of a study of the contour analysis algorithm developed by the authors for automatic recognition of objects in an image with their subsequent modeling in virtual simulators for training human-computer systems operators. The main distinctive feature of the developed contour analysis algorithm is the use of image convolution in four directions and the tracing procedure, which makes it possible to more accurately search for the contour of objects compared to other algorithms of this type. The results of the study of the algorithm are given. Based on this study, recommendations on the choice of the parameters of the algorithm are given. As a result of the analysis of three-dimensional modeling methods, it was concluded that for the effective implementation of three-dimensional graphics in virtual simulators for training human-machine system operators, it is advisable to use an algorithm for contour image analysis of external objects.

1. Introduction

Often, the operator of the human-machine system (HMS), including those used in the processing of images of external objects, requires not monotonous repetitive actions, but actions depending on the situation; therefore, assessing the future performance of the future operator only by the amount of knowledge replicated by him does not allow the HMS and the decision maker to process information in order to work independently as an HMS operator, therefore it is advisable to use the competence approach. Unlike the traditional training model, where the task of the future specialist is to master the sum of discrete knowledge and skills that are not always associated with real practical activities, the competence approach focuses on the result of training and places the personality of the future operator with her needs and abilities at the center of the process. And interests, which raises the question of the formation of an individual training trajectory.

From the view of a competence approach, the main focus is on the formation of needs for the constant replenishment, updating of knowledge, the improvement of skills and abilities, their consolidation and transformation into competences. The assimilation of knowledge and the formation of skills should be brought to the realization of their activities, but the training of operators of HMS at real technical facilities is a risky and expensive task. A novice operator can seriously damage or even destroy a technical object in the process of training. In addition, it is difficult to create a complex environment in which it is necessary to conduct training not only in managing a technical object, but
also in decision-making, and it is also difficult to ensure individualization of the preparation process. An alternative are virtual simulators that simulate real situations of operator activity.

Analysis of the current research on the use of virtual simulators in the process [1-6] showed that the main problem here is the transition from training on a virtual simulator to operating a real technical object. This is due to the insufficient approach of the training site of the future operator of the HMS to the real model of equipment, including the insufficient accuracy of the models in the virtual simulator.

In order to achieve the highest accuracy of models in the virtual simulator for training the operators of the HMS, it is advisable to use real external objects as the basis. To simulate the elements of the virtual simulator operators HMS on the basis of real objects it is necessary to analyze these images, which is hampered by the influence of negative external and internal factors. In this regard, it is proposed to apply the contour analysis algorithm developed by the authors.

Currently, there are a huge number of methods, models and algorithms that allow to process images of objects in the visible and infrared (IR) ranges. When analyzing images, contours of objects play a huge role. Outlines carry all the basic information about the elements of the image, which is weakly dependent on color and brightness.

In the algorithms considered in the sources [7-12], such algorithms as the Canny operator, the Roberts operator, the Sobel operator, the Gaussian laplacian, the Prewitt operator, etc. used to search for contours image convolution in 2 directions, this leads to the fact that some of the contour points of the object is suppressed.

The purpose of the study and its results presented in the article is the development of effective tools that provide high-quality training for HMS operators, including and the development of high-speed visualization algorithms for external objects. The contour analysis algorithm developed by the authors meets the criteria formulated by John Canny in 1986 [13].

2. Virtual simulator

A virtual simulator is an interactive system that functions on the basis of a mathematical model of the operator’s activity, which is the core of the training process and is responsible for the adequacy of the simulator – its completeness and accuracy of simulating the operation of the HMS [14]. It is the mathematical model of the operator’s activity in the virtual simulator that makes it possible for the operator to form an individual trajectory of the system’s development.

The results of the study showed that in virtual simulators based on the use of computer technology, are carried out the simulation of the systems of the controlled object and the dynamics of its interaction with the environment and objects that are in this environment and affect the functioning of the object, controlled by the operator. The simulation results are displayed on dashboards that contain the same instruments, indicators, and controls as the real object. The future operator becomes an element of the modeling circuit. Its impacts on controls are transmitted to the input of the object model, and as a result, this behavior of the object is reproduced, whatever it was in real conditions with the same control actions [15, 16].

The experience of building virtual simulators has shown that they consist of the following main components: control panel, control subsystem, dynamics subsystem and visualization subsystem. The general scheme of such a simulator is presented in Figure 1.

The control subsystem is designed to simulate the structural logic and control panels of the HMS. It provides the download of the control system files, visualization and interactive control of the virtual simulator elements using the control panel, as well as the calculation of the block diagrams of the control system in real time. The results of the calculation of the control system are transmitted to the dynamics subsystem.

The dynamics subsystem is designed to simulate the dynamics of virtual three-dimensional scenes based on external objects in real time. As a result of the calculation of the dynamics, data on the position and orientation of the scene elements and the HMS are generated, which are then transmitted to the visualization subsystem.
The visualization subsystem is intended for visualization of virtual three-dimensional scenes in real time. Also, one of the important features of the visualization subsystem is the recording of the training conducted by the operator and its subsequent reproduction for analyzing the correctness of the operator’s actions to accomplish the task. This makes it possible not only to assess the degree of preparedness of the operator, but also to correct the further plan of its preparation in accordance with the obtained results [17], which also ensures the implementation of the individual trajectory of training the operator of the HMS.

Virtual three-dimensional scenes are created in three-dimensional modeling systems based on drawings, photos and video materials, as well as other documents so that visually such models are as close as possible to real prototypes [18, 19].

The virtual simulators developed by the authors provide the maximum approximation of the training site of the future HMS operator to the real model of the equipment, the ability to document the operator's actions and their analysis, the possibility of immediate objective assessment of the quality of the task, modeling the situation as close as possible to real conditions.

In order to achieve the highest accuracy of models in the virtual simulator for training the operators of the HMS, it is advisable to use real external objects as the basis. Models based on real external objects also allow training of HMS operators on a specific real area.

To simulate the elements of a virtual simulator of operators based on real objects, it is not enough to have only images of these objects, it is also necessary to analyze these images, which are more efficient in time to perform in automatic mode, which is difficult because the effect of negative external and internal factors introduces uncertainty leading to image blur.

In this regard, algorithms and models are used to reduce the influence of uncertainty in image analysis. One of these algorithms the contour analysis algorithm developed by the authors.

3. Stages of the developed contour analysis algorithm

Preliminary stage. Convert image to grayscale.

The first stage of the algorithm is smoothing, since to obtain a stable result, noise filtering is necessary. For smoothing, a Gaussian noise filter is applied. The second stage of the algorithm is the search for gradients.

The algorithm applies four filters to define vertical, horizontal, and two diagonal borders. Each pixel is assigned a gradient value of its brightness. To do this, using the operator of determining the boundaries, we determine the vector of the gradient of the brightness of each point and the norm of this vector. The vector angle is rounded and takes one of the following values: 0, 45, 90, or 135 degrees. Such rounding will be necessary for the next stage.

The third stage of the algorithm is the suppression of non-maximums. Borders are pixels in which a local gradient maximum is reached in the direction of this gradient vector.
The fourth stage of the algorithm is double threshold filtering. All points designated as local maxima pass through two user-defined thresholds $T_{min}$ and $T_{max}$. If the value of a pixel gradient is higher than the upper threshold $T_{max}$, then the border in this pixel is reliable. If the gradient value of a pixel is below the lower threshold $T_{min}$, then the pixel is suppressed. Pixels whose gradients fall between two thresholds take a fixed average value and are processed at the final stage.

The final fifth stage of the algorithm is the trace of the ambiguity. At this stage, the pixels are processed, the gradients of which are in the range between the thresholds. This is achieved using the trace procedure developed by the authors. All pixels that did not fall into the group of boundary pixels following the results of the procedure are suppressed [20].

4. Features of the image blurring procedure in the developed algorithm

One of the main filters applicable to image blur is a Gaussian filter. The problem of boundary pixels in the developed contour analysis algorithm is solved as follows. You must create a temporary image with the dimensions:

$$\text{width} + \left(\text{dim}+1\right)/2, \text{height} + \left(\text{dim}+1\right)/2,$$

where width and height - width and height of the filtered image, dim – dimension of the convolution matrix.

The input image is copied to the center of the image, and the edges are filled with the extreme pixels of the image. Blur is applied to the intermediate buffer, and then a new value is extracted from it. The application of this method is shown in Figure 2.

![Figure 2. Blur using intermediate magnified image.](image)

In order to determine the color of the pixel, which is the center of the core, it is necessary to multiply the weights of the core with the corresponding color values of the edited image. After that, the results are summarized [21].

The resulting image will be blurry compared to the original, as the color of each processed pixel “spread” among neighboring pixels.

Anti-aliasing suppresses noise, supporting the requirement that the pixels look like their neighbors. By reducing the weights for distant pixels, you can be sure that for them this requirement will not be so strict. As a result of the study, recommendations were made on the choice of the parameter $\sigma$:

1) If $\sigma$ is small (for example, $<1$), then smoothing will give a minor result, since the weights of all pixels that are not in the center will be very small.

2) With larger $\sigma$ of neighboring pixels, the weighting factors when applying a weighted average scheme will be larger, which, in turn, means that the average value will strongly seek agreement with its neighbors – this will be a good estimate of the pixel value, and due to blurring, a large part of the noise.

3) A nucleus with a large $\sigma$ leads to the fact that most of the image elements will disappear along with the noise.

If $\sigma$ is too small, then only one element of the matrix will be nonzero. If it is large, then the size of the convolution matrix should also be large, otherwise the contribution of the pixels, which should be included with significant weight coefficients, will not be taken into account [22].
5. The originality of the developed algorithm consists in the procedure for calculating the gradient in each pixel of the image

The main scientific result obtained by the authors during the development of the algorithm is the procedure for convolving images in 4 directions.

Consider $Z$ matrix size of $3 \times 3$ having brightness values only in the vicinity of a certain pixel:

$$Z = \begin{bmatrix} z_1 & z_2 & z_3 \\ z_4 & z_5 & z_6 \\ z_7 & z_8 & z_9 \end{bmatrix}.$$

To calculate the magnitude of the gradient at a particular point in the image, it is necessary to use both components $G_x$ and $G_y$ together:

$$G = \sqrt{G_x^2 + G_y^2},$$

where $G_x$ and $G_y$ are two matrices, where each point contains approximate derivatives with respect to $x$ and $y$; $G$ is the gradient value in pixel $z_5$.

The Robinson operator is used for speed calculations, but he loses to other algorithms in noise sensitivity. The contour lines with this method of image contour extraction are thinner than with some other methods. The algorithm is based on using only one mask, which is rotated in eight main directions: north, north-west, west, south-west, south, southeast, east and northeast.

The size of the boundary is defined as the maximum value found using the mask. The direction determined by the mask gives the maximum value. For example, the mask $r_0$ corresponds to the vertical border, and the mask $r_5$ corresponds to the diagonal one. It can also be noted that the last four masks are a mirror reflection with respect to the central axis of the matrix [23]:

$$r_0 = \begin{bmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{bmatrix}, \quad r_1 = \begin{bmatrix} 0 & 1 & 2 \\ -1 & 0 & 1 \\ -2 & -1 & 0 \end{bmatrix}, \quad r_2 = \begin{bmatrix} 1 & 2 & 1 \\ 0 & 0 & 0 \\ -1 & -2 & -1 \end{bmatrix}, \quad r_5 = \begin{bmatrix} 2 & 1 & 0 \\ 0 & 1 & 0 \\ -1 & -2 & -1 \end{bmatrix}, \quad r_6 = \begin{bmatrix} 1 & 2 & 1 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad r_7 = \begin{bmatrix} 1 & 2 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 1 \end{bmatrix}.$$

6. Tests of the developed contour analysis algorithm

A series of tests of the developed contour analysis algorithm implemented in the visualization subsystem (Figure 1) was carried out. The Robinson operator was used to calculate the gradient. Figures 3 and 4 show examples of image processing with a modified algorithm [24-25].

![Figure 3. Image processing tank.](image-url)
7. Simulation
Due to the analysis of the image, there are contours of objects and terrain, on which three-dimensional models are built for the virtual simulator of training the operators of HMS. There are various methods of three-dimensional simulation [26]:

1. Polygonal simulation. The disadvantage of polygonal simulation is that all objects must consist of tiny flat surfaces, and polygons must be very small, otherwise the edges of the object will have a faceted appearance.

2. Spline simulation. Models are smoothly shaped, and therefore, this method has been widely used in creating organic models, such as plants, people, animals, etc. Advantages of spline simulation are the ability to change the shape of a particular spline at any time and preserve quality when scaling.

3. NURBS simulation (Non-Uniform Rational B-Spline). Also allows you to create models with smooth shapes. NURBS-curves are effectively used to build commercially available industrial products, which are simultaneously characterized by precise performance and streamlined shapes. One of the main advantages of modeling based on NURBS curves is the ability to transform the model into a polygonal one with subsequent automatic changes. The negative aspects of NURBS modeling include: the complexity of animating models, increasing the rendering time.

4. Simulation by metaspheres. Its peculiarity is that the model is built from three-dimensional objects of a smoothed closed shape (metaspheres), which, when in contact with each other, are automatically merged by parts of the contacting surfaces.

5. Digital sculpture (3D-sculpting). It is an imitation of the process of “sculpting” a three-dimensional model, that is deforming its polygonal mesh. In fact, this is also the most polygonal modeling, but aimed at creating mostly complex biological organisms.

6. MEL-simulation (Maya Embedded Language) is another three-dimensional simulation method implemented in the Maya program. The principle of creating models by this method lies in the fact that formulas for constructing curves and surfaces are specified in an absolutely arbitrary way. Using MEL commands, curve and surface generators are constructed using parametric formulas.

Separately, it is worth to identify computer-aided design systems (CAD), which are used to create three-dimensional models for industrial use. They are designed to create exact copies of real objects. The peculiarity of this simulation is that in order to create a model, it is not polygons that are used, but solid forms. There are 3 methods of simulation using CAD [26, 27]:

1. Parametric simulation. It allows for a short time to mathematically simulate various objects and avoid fundamental errors.

2. Solid simulation. Solid simulation is ideal for creating solid three-dimensional models of simple form: gears, engines, etc., but not applicable to creating soft: crumpled clothes, animals, etc.

3. Surface simulation. It is used to create surfaces of complex shapes: cars, airplanes, etc. The model is built from different surfaces, which give the desired shape, and then connected with each
other, for example, smooth transitions, and cut off the excess. Thus, the shape of the desired shell of the object is assembled from several surfaces.

8. Conclusion

The use of images of real external objects in the virtual simulator for training the operators of the HMS provides a simulation of the situation as close as possible to the actual conditions, which undoubtedly makes the preparation process more efficient. Such models also allow for the training of operators of HMS on a specific real terrain.

The developed algorithm of contour analysis with an extremely insignificant increase in the processing time of an image of an object results in a significant gain in its quality (15% more contour points are defined than in standard algorithms), which is important for representing external objects in the virtual simulator for training HMS operators.

The advantages of the Canny algorithm are:
- Minimization of the multiple responses to the filter;
- Increase the value of the signal-to-noise ratio;
- Improved recognition performance on noisy images, due to anti-aliasing.

The disadvantages of the algorithm include:
- The lack of clear criteria for the selection of thresholds, which leads to the distortion and loss of some of the real contours and to the appearance of false contours;
- Rounding the corners of the borders of objects, which leads to damage or destruction of the borders at the junction points.

However, these disadvantages are not significant.

The test results of the upgraded algorithm Canny:
1. Software implementation Canny algorithm allows you to highlight the technological facilities, as clear, and the blurred image.
2. The main interference in the analysis of images are physical background surface irregularities as well as the reflection of light sources on the surface.
3. Recommended parameters of the algorithm for clear images: $T_{\text{min}} = 20$, $T_{\text{max}} = 45$, $\sigma = 1$.

Recommended parameters of the algorithm for blurry images: $T_{\text{min}} = 5$, $T_{\text{max}} = 15$, $\sigma = 0.01$ [28].

As a result of analyzing three-dimensional simulation methods, it was concluded that to effectively implement three-dimensional graphics in virtual simulators for training operators of the HMS, to adequately consume computational resources and to enable the formation of an individual trajectory for operator preparation, it is not enough to use any one method of three-dimensional modeling. Compliance with the simulated object and the requirements for the model of this object. For example, when creating models of simple form, it is better to use polygonal modeling. To get a smooth shape of simple objects, you should apply spline or NURBS-simulation, or polygonal using smoothing tools. When creating complex organic objects, it is more convenient to use digital sculpture. When it is necessary to create an exact model with the necessary gaps and taking into account the physical properties of the material, then CAD methods are most suitable. When creating complex models, the above-described simulation methods should be used together, as this will speed up the simulation process.

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