Software and hardware system for diagnostics of deposits inside the vortex chamber

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Abstract. This paper is devoted to the development of software for the system of visualization of deposits inside vortex chambers and the creation of algorithms for improving the quality of visualization. As part of the work, software for the microcontroller, which manages the entire hardware part, was created. An application for PC for visualizing images from the camera to the experimenter has been developed. Algorithms for correcting the distortion and subtracting the background are implemented for better analysis of the geometry of deposits.

1. Introduction
Vortex chambers are used in many energy systems, hydrocarbon furnaces and process furnaces. The study of aerodynamic processes inside vortex chambers is an urgent task [1-2]. Experiments on such installations are accompanied by complex conditions inside the chamber itself. High temperature leads to overheating of optical and electronic components of diagnostic systems and intense thermal radiation from surfaces, which makes it difficult to use standard video surveillance systems. At the moment, there are many video cameras that allow you to observe in confined spaces, such as USB cameras and video endoscopes [3]. These devices are sealed and can provide surveillance without interference. However, they are not able to withstand high temperatures and show high-quality images under intense thermal radiation. Such devices do not have a high-power illumination to illuminate large spaces, but are designed for inspection of small cavities, such as cylinders of internal combustion engines. The presence of highly polluting optical surfaces of deposits in the studied volume also imposes increased requirements on the system of diagnostics of deposits inside the vortex chambers. This significantly affects the complexity of the design of the optical components of the camera and forces the use of additional processing algorithms to improve image detail. The purpose of this work is to develop software for a system for diagnosing deposits inside a vortex chamber designed for operation at high temperatures, as well as in an environment of heavy contamination of the surfaces of optical devices.

2. Method description
The functional diagram of the developed visualization system is shown in figure 1. The design of the visualization system provides for cooling the body, observation through a small-diameter hole using a photodetector 4, and illumination of the inner cavity of the vortex chamber with an illuminator 5. It also monitors the system status and protects against overheating using temperature sensors 6, to control the hardware of the visualization system, a programmable microcontroller 2 is used, installed in the external box. The system is managed and received images are recorded on a computer 1. The computer, microcontroller, and camera are connected to each other over an Ethernet network.

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The camera is equipped with a lens with a complex optical scheme that allows you to observe through small holes. This lens creates a strong negative distortion, also called the "fish eye" effect, which makes it difficult to evaluate correctly the geometry of objects observed inside the studied area. In this regard, without preprocessing, the footage from the video camera gives little information. It is necessary to implement algorithms to improve the quality of the observed image and embed them in the computer software.

![Diagram](image)

**Figure 1.** Functional diagram of the developed visualization system:
1 – computer, 2 – microcontroller, 3 – microcontroller expansion Board, 4 – photodetector, 5 – illuminator with electronic power control relay, 6 – temperature sensors.

Pulsed illumination of the led allows you to get more lighting power and not overheat the led, which is subject to heating from the environment. But this imposes additional requirements on the calibration of the on-time of LED as backlight must be synchronized with the camera, that is, the backlight should turn on at the beginning of the camera frame and off immediately after. This allows you to use lighting more effectively. The LED is powered by a power supply. There is a delay between the power-on signal coming to the power driver and the LED turning on. It must be taken into account before opening the camera shutter. Controlling the camera lighting and shutter allows you to take single frames at specific times and control the video frame rate on the user interface.

To correct the distortion, it is necessary to determine the calibration coefficients for this lens [3]. Calibration of the camera is the task of obtaining internal and external parameters from the received photos. Calibration of the camera allows you to correct distortion in images. Typically, a column vector of the form \([u, v]\) is used to represent the 2D coordinates of a point on the camera plane, and \([x_\omega, y_\omega, z_\omega]\) is used to set the position of the 3D point in world coordinates. They are linked by a formula:

\[
\begin{bmatrix}
u \\
v
\end{bmatrix} = A[R \ T]\begin{bmatrix}x_\omega \\
y_\omega \\
z_\omega
\end{bmatrix},
\]

where \(A\) is the internal calibration matrix, which contains 5 significant parameters. These parameters correspond to the focal length, pixel angle, and intersection point of the image plane with the optical axis that coincides with the center of the photo. And it is represented as:

\[
A = \begin{bmatrix}
\alpha_x & 0 & 0 \\
0 & \alpha_y & 0 \\
0 & 0 & 1
\end{bmatrix}
\]

\(R\) is a \(1 \times 3\) vector or a \(3 \times 3\) rotation matrix, and \(T\) is a \(3 \times 1\) transfer vector. These are external calibration parameters that define the coordinate transformation, or external calibration parameters that set the camera position in the world coordinate system. These parameters are directly related to the
scene being photographed, so each photo has its own set of these parameters. All these parameters can be obtained using an algorithm developed by Zhengyou Zhang and based on the use of a flat calibration object in the form of a chessboard [4].

In the presence of external noise or thermal illumination, the quality of visualization is greatly reduced. To improve the visual quality of the applied differential method of image registration, there are algorithms of background subtraction. The system registers two images: one without the use of an illuminator to capture external radiation, and the second with the use of an illuminator to highlight the geometry of objects. The first image contains the intensity distribution without $I_b$ illumination. The second image $I_l$ contains the sum of the intensity of illumination scattered on the surface of the observed objects $I_f$ and the background glow $I_b$. In this case, to obtain the intensity distribution $I_f$, it is necessary to coordinate the energy function of the photodetector and the intensity of the illuminator radiation and perform a pixel-by-pixel subtraction of the second frame from the first:

$$I_f = I_l - I_b.$$ (3)

As a result, you will get an image with only scattered radiation of the illuminator registered on it. This makes it possible to significantly increase the information content of the received images when visualizing high-temperature processes.

3. Experimental results
The software of the Iskra JS microcontroller based on the 32-bit ARM Cortex-M4 microcontroller was developed. To work out various scenarios of the system, several modes of operation of the visualization system hardware were implemented: video recording, standby mode, and loading new parameters of the image frame. It uses a microcontroller to control the camera shutter [5]. This is implemented by sending a synchro signal from a specific pin of the microcontroller [6] to the camera contact DMM 25GP031-ML, which is responsible for external synchronization. The microcontroller connected to the relay of the led power supply is also responsible for switching on the lighting. It provides full illumination of the frame, turning on and off the illuminator. There is a small time delay between the power-on signal coming to the driver and the led turning on [7], which also needs to be taken into account before opening the camera shutter (Fig. 2). To monitor the system temperature, the ds18b20 temperature sensors are interrogated over the MODBUS Protocol, which are located on the same line without additional power.

**Figure 2.** Delay of 20-40 MS for triggering the LED power supply.

Communication with the computer is implemented using the Ethernet Shield expansion Board (Fig. 1, 3). A communication Protocol over TCP-IP is implemented, which includes the code of the sending or response, data, and the checksum of the entire shipment. The microcontroller performs the function of a server, waiting for a request from the user computer to execute a command. There are three main types of commands: "start video recording", "load new parameters" of the frame, and "stop video recording". "Start" and "stop" are responsible for enabling the synchro signal mode for the camera and lights, starting or ending data transfer from the camera to the computer. The message with
the command "loading new parameters" contains information about the time between frames and a flag encoding whether to use the illuminator or not.

A PC application that visualizes the image from the camera in real time, and also allows you to configure the frame parameters by transmitting the settings directly to the photodetector has been developed. The user interface provides access to the lighting control. The current state of temperatures that the application receives from the microcontroller is shown to the user. The microcontroller sampling period is configured in the configuration file.

To correct the distortion, we used the "calibrate Camera" function from the OpenCV image processing library, which returns a matrix of coefficients that characterize this camera and the distortion coefficients. To use this function, you must specify points that are located on a straight line in the real world, but on a distorted image they are located on a certain curve. To do this, you can take a photo of the chess Board and find the corners of the chess cells on it [4, 8]. The automatic and manual method of searching for corners is implemented. The automatic method (Fig. 3) analyzes the original image of the chessboard (Fig. 3 a), using the image of one corner as a template for searching (Fig. 3 b). The algorithm constructs a cross-correlation function (Fig. 3 c) and finds the positions of the angles (Fig. 3 d), which are then passed to the function for calculating the calibration coefficients.

![Figure 3. Automatic search for corners of chess cells.](image)

The manual angle search method is implemented for analyzing images of poor quality. On the original image (Fig. 4 a), the user manually applies the location of the angle (Fig. 4 b). Next, the array of all found corners is sorted in order, as they are located on the chessboard. To do this, an algorithm for constructing a convex hull is implemented, which finds an array of points on the outer side, whose upper and lower rows are determined by the largest and smallest vertical coordinates (Fig. 4 c). Next, the found points are excluded from the total array of points and this algorithm is repeated to find all rows of corners of the chessboard. The resulting sorted points are passed line by line to the function for calculating the distortion coefficients [9].

![Figure 4. A manual search of the corners of the chess squares.](image)
After getting the camera and distortion coefficients, we substitute them in the formula:

\[ u_{\text{Corrected}} = u(1 + k_1 r^2 + k_2 r^4 + k_3 r^6) \]  
\[ v_{\text{Corrected}} = v(1 + k_1 r^2 + k_2 r^4 + k_3 r^6) \]  

where \( u, v \) are the coordinates of the points in the original image, \( k \) are the distortion coefficients, and \( r \) is the distance to the point \( u, v \). After all the transformations, we get an image with corrected distortion (Fig. 5).

![Image](image.png)

**Figure 5.** The correction of the distortion of the image. \( a \) – the original image, \( b \) – the corners of the chess cells line by line, and \( c \) – the image with corrected distortion.

To improve the visual quality of images registered by the system, the background subtraction method is implemented [10]. To do this, take a picture with the light turned off, which shows only the thermal illumination of the observed scene. After that, the illuminator turns on and a second picture is taken. This is implemented by enabling and disabling the illuminator with a command for the microcontroller. At the end of the second snapshot, the first one is subtracted. This results in a more contrasting image. This allows you to separate the thermal illumination on the camera and observe only the areas of light and shadow to improve the quality of visualization. When this mode is enabled, the refresh rate of image frames on the user interface decreases as a result of combining multiple frames. This should be taken into account when observing fast-moving processes.

**Conclusions**

A software and hardware system for visualizing deposits inside the vortex chamber has been developed. The software microcontroller hardware-software complex for the visualization system, which provides control of the entire system, has been developed. Software for a personal computer that provides remote monitoring of images from a video camera and control of the system operating modes has been developed. The communication protocol between the microcontroller and the computer is implemented. The microcontroller accepts commands from the computer and accepts new operation parameters. The microcontroller also controls the camera shutter, switches on the illuminator according to algorithms that depend on commands received from the computer, interrogates temperature sensors and, if critical values are exceeded, signals this to the operator on the computer.

The algorithms for subtracting the background and correcting distortion in the received images were implemented. As a result of the developed algorithms, it was possible to improve the quality of visualization of the technological process under conditions of limited lighting and difficult operating conditions.

The developed software and hardware system for diagnostics of deposits inside the vortex chamber has successfully passed full-scale tests for visualization of deposits inside the vortex chamber with a temperature of more than 1000°C.
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