Camera and auxiliary sensor calibration for a multispectral panoramic vision system with a distributed aperture

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Abstract. The constructions of test objects for calibrating cameras of the visible and infrared ranges that make up the panoramic survey optoelectronic system, as well as calibration algorithms for auxiliary inertial microelectromechanical sensors for determining the angular position are considered. The results of image forming from a virtual camera that realizes the transfer of the centre of the generated panoramic video image to the observer’s placement point are presented. As part of the field experiment with cameras of the visible and long-wave infrared ranges, it was shown that calibration of the sensors of the panoramic system with a distributed aperture at a known distance to the objects of observation results in an error of combining multi-spectral images of not more than 3′.

1. Introduction

The quality of video panoramas that are formed according to the information from several separated cameras with intersecting fields of view is determined by the quality of both the optical systems and the photosensitive elements of cameras and the errors in estimating the parameters of their mathematical models. While photographing remote objects from a moving vehicle with a distributed panoramic system (DPS), the error in stitching of images that make up the panoramic frame also depends on the accuracy of estimates of the distance to the objects of observation and the orientation angles of the camera sighting lines relative to the horizon plane. Therefore, the calibration of not only cameras, but also auxiliary sensors of the DPS, is an obligatory stage in the development of panoramic survey optical-electronic systems.

2. Multispectral camera calibration

2.1. Principles of test objects construction for calibration of multispectral cameras

The classical method of camera system calibration for estimating the intrinsic matrix, the vectors of lens distortion coefficients, the rotation matrices of the camera coordinate systems (CS) and the translation vectors of their optical centres relative to the reference camera CS is the shooting of test objects (TO) with a priori known geometric characteristics from different angles. For example, spheres [1], as well as planar templates with images like "chessboard", "mesh" or "point field" [2, 3] or with marks in the form of concentric circles with radial markers [4], can act as such TOs.
Calibration of multispectral cameras, for example, short-wave (SWIR) and long-wave (LWIR) infrared (IR), as well as visible ranges, requires a special test object, which images are contrasty in all specified spectral ranges at once. In the production of such TO, the following constructions are used as a rule, either constructions with a heated light plate on which not transmitting thermal radiation geometrical elements are ordered [5, 6], or constructions, consisting of two plane-parallel plates, a dark lower and a light upper, containing an ordered set of holes, with the heated bottom plate [7]. For example, in this work the first type of TO with image inversion of LWIR camera is used for calibration of television (TV) and LWIR cameras of DPS (figure 1).

This TO allows to calibrate multispectral cameras, for example, using functions from the OpenCV library or the Camera calibration toolbox for MATLAB.

2.2. Strategy of multispectral cameras calibration
While designing the DPS with a limited number of cameras, it is necessary to obtain the largest field of view of the panoramic frame and the minimum optical parallax. For this purpose, the angular size of the intersection of the camera field of view should be minimized.

To ensure a low estimation error of the distortion coefficients of the lens and the intrinsic matrix of the camera, the shooting of TO is performed from different angles; at the same time, its images should be located both in the center of the frame and along the periphery (figure 2). This provides an approximately uniform distribution of keypoints across the frame.

When TO images are placed mostly in one part of the frame (figure 3), that is typical, for example, for calibrating stereo pairs with a large base, the absence of keypoints in another part increases the deviation of the intrinsic matrix elements and radial distortion coefficients compared to their approximately uniform distribution over the frame (figure 4). For this reason, the authors applied the following calibration strategy.

1. As our DPS cameras were focused at infinity, the physical dimensions of the TO were selected based on the condition of ensuring that the width of the TO image is at least a half of the frame width when it is located on the near border of depth of field of each camera. For the DPS layout, the size of the TO pattern cell was selected 15×15 cm.

2. For each $i$-th camera of the DPS, $i = 1, 2, ..., N_{\text{cam}}$ where $N_{\text{cam}}$ is the number of cameras, only intrinsic matrices $K_i$ and lens distortion coefficients were initially estimated when the universal TO (figure 1) was located in different parts of the frame (figure 2).

3. Due to the small angular dimensions of DPS cameras intersection of the fields of view, external parameters (rotation matrices $R_i$ and translation vectors $t_i$ of $i$-th camera relative to the CS of the reference camera) were estimated using a previously calibrated auxiliary camera [8] (figure 5).
Figure 3. Frames with TO images are predominantly in the left part of the frame (left) and the distortion vector field obtained as a result of calibration in the Camera calibration toolbox for MATLAB (right).

Figure 4. Frames with TO images are in different parts of the frame (left) and the distortion vector field obtained as a result of calibration in the Camera calibration toolbox for MATLAB (right).

Figure 5. The idea of calibrating with an auxiliary camera 3: TO 1 and TO 2 are positions of TO for the joint calibration of cameras 1 and 2.

4. According to the estimated transformation matrices \( T_{31} = \begin{bmatrix} R_{31} & t_{31} \\ \mathbf{0}^T & 1 \end{bmatrix} \) and \( T_{32} = \begin{bmatrix} R_{32} & t_{32} \\ \mathbf{0}^T & 1 \end{bmatrix} \) the matrix \( T_{12} = T_{31}^{-1}T_{32} \) was estimated, from which the extrinsic parameters \( R_{12} \) and \( t_{12} \) were extracted.

3. Calibration of auxiliary inertial sensors

3.1. Microelectromechanical accelerometers calibration

It is known [9] that in the forming of spherical or cylindrical panoramas it is necessary to know the angle of shooting: roll and pitch of DPS cameras CSs relative to the plane of the horizon. These angles can be obtained using inertial measurement units (IMU) that are built on microelectromechanical sensors (MEMS) of acceleration (three-axis accelerometers, TA) and angular velocity (three-axis gyroscopes, TG). The error in determining the roll and pitch from the IMU signals depends largely on the accuracy of estimating the calibration parameters of TA and TG.

A simplified mathematical model of a MEMS TA signals (it does not take account of non-orthogonality of the axes of sensitivity and temperature dependence of the calibration parameters) in the resting state is [10]:
With the known parameters Mahony [14] algorithm.

3.3. Angular coordinates estimation with IMU

In the presence of a special equipment, which allows to establish TA at the $N \geq 6$ fixed positions with a priori known projections $g$, for the estimation of the unknown $K_g$ and $b_a$ the overdetermined system of equations is solved:

$$Gp_a = a,$$  \hspace{1cm} (1)

where $G = [G_1, G_2, \ldots G_N]^T$ consists of a priori values of gravity vector projections at $t$-th position, $G_t = \begin{bmatrix} g_{xt} & 1 & 0 & 0 & 0 \\ 0 & 0 & g_{yt} & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & g_{zt} \end{bmatrix}$, $t = 1, 2, \ldots N$, and $a = [a_1, a_2, \ldots, a_3]^T$ is the vector of TA measurements.

Linear pseudo-solution of (1) is a vector

$$p_a = G^+ a,$$  \hspace{1cm} (2)

where $G^+ = (G^T G)^{-1} G^T$ is pseudoinverse Moore – Penrose matrix.

In the absence of special equipment the parameters $K_g$ and $b_a$ are estimated by the least squares method from the overdetermined system of $N$ nonlinear equations for arbitrary positions of TA [11]:

$$\{(a_x-b_{ax})k_{ax}\}^2 + \{(a_y-b_{ay})k_{ay}\}^2 + \{(a_z-b_{az})k_{az}\}^2)^{0.5} = g_0,$$

where $g_0$ is a gravity vector module (for most TA with digital interfaces its value is normalized: $g_0 = 1$).

3.2. Microelectromechanical gyroscopes calibration

A simplified mathematical model of the MEMS TG signals (by analogy with the MEMS TA that does not take into account the non-orthogonality of the sensitivity axes) can be represented as [12]:

$$w_t = K_g w_{it} + b_a(t, T) + n_{it},$$  \hspace{1cm} (3)

where $K_g = \text{diag}\{k_{gx}, k_{gy}, k_{gz}\}$ is a diagonal matrix of gains, and $w_t = [w_{ix}, w_{iy}, w_{iz}]^T$, $w_{it} = [w_{ixt}, w_{iyt}, w_{itz}]^T$, $b_a(t, T) = [b_{ax}(t, T), b_{ay}(t, T), b_{az}(t, T)]^T$ and $n_{it} = [n_{ixt}, n_{iyt}, n_{itz}]^T$ are respectively vectors of TG measurements, true angular velocities, gyro biases and angle random walks (ARW), that depends on time discrete $t$ and temperature, and flicker noise. ARW is characterized by Allan variance [13].

Assuming that during the calibration the ARW value can be neglected and the temperature is constant, the parameter $b_a(t, T)$ from (3) can be eliminated and the $K_g$ can be estimated if the calibration triaxial rotation platform is set on a horizontal surface and TG turns around each of its axes in the directions of (+) and against (–) clockwise with the same angular velocity $\omega_0$ and returning to the initial position:

$$k_{gi} = 0.5(\{ M\{w_i^{-}\}\} + |M\{w_i^{-}\}|)/\omega_0, i = \{x, y, z\},$$

where $M\{\cdot\}$ is a mean value calculation.

3.3. Angular coordinates estimation with IMU

With the known parameters $K_g$ and $b_a$ at the resting state we can estimate the initial roll $\phi_0$ and pitch $\theta_0$ using the MEMS TA signals by the formulas:

$$\phi_0 = \text{atan}2(g_y, g_x), \theta_0 = \text{atan}2(g_z, [g_x^2 + g_y^2]^{0.5}),$$  \hspace{1cm} (4)

where $g = K_g^{-1}(a - b_a)$. The current values of the $b_a(t, T)$ vector can be estimated with averaging TG measurements. Current values of $\phi$ and $\theta$, at time discrete $t$ can be estimated, for example, with the Mahony [14] algorithm.
4. Compensation the rotation of the auxiliary sensors coordinate systems relative to the coordinate system of the reference camera

4.1. Estimation of rotation of IMU coordinate system relative to the reference camera coordinate system

While installing the IMU in the body of the DPS reference camera, it is also necessary to take into account the noncollinearity of the axes of their CSs. The calculation of the rotation matrix \( R_{\text{cam-IMU}} \) between the camera CS and the IMU CS can be based on shooting from the reference camera a series of frames with planar TO in a priori known \( m = 1 \ldots M, M \geq 1 \), angular positions:

\[
\begin{bmatrix}
cos \varphi_m & - \sin \varphi_m & 0 & 1 \\
\sin \varphi_m & \cos \varphi_m & 0 & 0 \\
0 & 0 & 1 & 0 
\end{bmatrix}
\]

where \( R_{\text{IMU}} \) is the rotation matrix of the camera CS relative to the TO CS in the position \( m \), \( R_{\text{TO}} \) is the rotation matrix which characterizes \( m \)-th TO position during the calibration.

In the presentation through the Rodrigues – Hamilton parameters [15], equation (5) takes the form:

\[
\begin{bmatrix}
cos \varphi_m & - \sin \varphi_m & 0 & 1 \\
\sin \varphi_m & \cos \varphi_m & 0 & 0 \\
0 & 0 & 1 & 0 
\end{bmatrix}
\]

where quaternion elements \( q_w = \cos(0.5\psi)\cos(0.5\theta)\cos(0.5\varphi) + \sin(0.5\psi)\sin(0.5\theta)\sin(0.5\varphi) \), \( q_x = \cos(0.5\psi)\sin(0.5\theta)\cos(0.5\varphi) - \sin(0.5\psi)\cos(0.5\theta)\sin(0.5\varphi) \), \( q_y = \sin(0.5\psi)\cos(0.5\theta)\cos(0.5\varphi) + \cos(0.5\psi)\sin(0.5\theta)\sin(0.5\varphi) \), \( q_z = \cos(0.5\psi)\cos(0.5\theta)\sin(0.5\varphi) - \sin(0.5\psi)\sin(0.5\theta)\cos(0.5\varphi) \),

are associated with the elements \( R_{ij}, i, j = 1..3 \), of rotation matrices \( R \) by expressions:

\[
q_w = 0.5[1 + R_{11} + R_{22} + R_{33}]^{0.5}, \quad q_x = 0.25[R_{31} - R_{13}] / q_w, \quad q_y = 0.25[R_{12} - R_{21}] / q_w, \quad q_z = 0.25[R_{23} - R_{32}] / q_w,
\]

where \( \psi, \theta \text{ and } \varphi \) are respectively yaw, pitch and roll, \( q_w \) and \( [q_x, q_y, q_z]^T \) are respectively scalar and vector parts of quaternion, «\( \bullet \)» and «\( ^* \)» are respectively quaternion multiplication and conjugation.

The pseudo-solution of the overdetermined system of \( M \) equations (6) (see Appendix A) is a vector \( v_{\text{cam-IMU}} \) that consists of the quaternion \( q_{\text{cam-IMU}} \) elements

\[
v_{\text{cam-IMU}} = (\mathbf{Q}_{\text{IMU}}^{-1} \mathbf{Q}_{\text{IMU}}^*)^T v
\]

and corresponding to its vector rotation matrix

\[
\mathbf{R}_{\text{cam-IMU}}(v) = \begin{bmatrix}
1 - 2(v_y^2 + v_z^2) & 2(v_y v_x - v_z v_y) & 2(v_y v_z + v_x v_y) \\
2(v_x v_y + v_z v_x) & 1 - 2(v_x^2 + v_z^2) & 2(v_x v_z - v_y v_x) \\
2(v_x v_z + v_y v_x) & 2(v_x v_y + v_z v_x) & 1 - 2(v_x^2 + v_y^2)
\end{bmatrix}.
\]

The vector \( v \) in (7) is obtained by stacking of the vectors \( v_m = [q_{\text{TO}}^m, q_{\text{cam}}^m, q_{\text{IMU}}^m]^T \) that are composed of the quaternion elements \( q_m = q_{\text{TO}}^m \bullet q_{\text{cam}}^m, m = 1..M \):

\[
v = [v_1^T, v_2^T, \ldots, v_M^T]^T.
\]

The \( \mathbf{Q}_{\text{IMU}} \) matrix is obtained by vertical stacking of the \( \mathbf{Q}_{\text{IMU}}^m \) matrices, and each of them is composed of \( q_{\text{IMU}}^m \) quaternion elements according to the rule [15]:

\[
\mathbf{Q} = f(q^*) = \begin{bmatrix}
q_0^* & q_1^* & q_2^* & q_3^* \\
q_1^* & q_0^* & q_3^* & -q_2^* \\
q_2^* & q_3^* & q_0^* & -q_1^* \\
q_3^* & -q_2^* & q_1^* & q_0^*
\end{bmatrix}
\]

\[
\begin{bmatrix}
g_0 & g_1 & g_2 & g_3 \\
g_1 & g_0 & g_3 & -g_2 \\
g_2 & g_3 & g_0 & -g_1 \\
g_3 & -g_2 & g_1 & g_0
\end{bmatrix}.
\]
4.2. Mutual calibration of the range meter and the reference camera of DPS

It is known that when we form a panoramic frame of DPS and shoot objects at different distances, the information about the distance to them is needed. Such information can be obtained from data from the lidar [16] or, in its absence, according to data from the stereo pair and the source of laser illumination, which forms a grid of points. If the reference camera of the DPS acts as the reference camera of the stereo pair, then the CSs of the range meter and the RPS are matched. If a lidar is used, it is necessary to perform its mutual calibration with the DPS reference camera in order to evaluate the rotation matrix $R_{\text{lidar}}$ and the translation vector $t_{\text{lidar}}$ of the lidar CS relative to the SC of the reference camera [17, 18].

5. Algorithm of the panoramic image construction from distributed cameras, IMU and laser range meter information

In [19, 20] we considered algorithms for the forming an observer’s personal region of interest (RoI) from DPS cameras information, in which spherical panorama is constructed, the distance between the principal points of the cameras is neglected and only the rotation matrices of their CSs are taken into account. In the presence of range meter information from the lidar or a source that forms a field of laser illumination points, the quality of image stitching in the RoI is improving [16].

Let we have the results of measurements of the laser range meter (LRM) – $N_{\text{LRM}}$ angular directions $(\alpha_j, \beta_j)$, for which distances to observed objects $D_j$, $j = 1, 2, ..., N_{\text{LRM}}$, are known. The algorithm of RoI image construction, which takes into account the distance information to $N_{\text{LRM}}$ points of the scene, contains the following steps.

Initialization

1. Calculation of quaternions $q_{uv0}$, giving the initial angular directions to RoI pixels with coordinates $(u, v)$ [19]:

$$q_{uv0} = [\cos(0.5\alpha_u)\cos(0.5\beta_u), \cos(0.5\alpha_u)\sin(0.5\beta_u), \sin(0.5\alpha_u)\cos(0.5\beta_u), \sin(0.5\alpha_u)\sin(0.5\beta_u)]^T,$$

$$\alpha_u = \arctan(x_{uv}), \quad \beta_v = \arccos\left[\frac{y_{uv}}{\sqrt{x_{uv}^2 + y_{uv}^2 + z_{uv}^2}}\right],$$

$$x_{uv} = (2u/W - 1)/3, \quad y_{uv} = (2v/H - 1)/3, \quad z_{uv} = 1,$$

where $W$ and $H$ are respectively the width and height of the RoI in pixels, $\Delta\varphi_u$ and $\Delta\varphi_v$ are its horizontal and vertical angular dimensions, $\alpha_u$ and $\beta_v$ are the azimuth and elevation of the line connecting the center of the virtual unit sphere and pixel $(u, v)$ of RoI plane.

2. Calculation of the quaternions $q_{LRMj}$, $j = 1, 2, ..., N_{\text{LRM}}$, determining the angular directions to the points of the laser illumination or the lidar scanning directions:

$$q_{LRMj} = [\cos(0.5\alpha_j)\cos(0.5\beta_j), \cos(0.5\alpha_j)\sin(0.5\beta_j), \sin(0.5\alpha_j)\cos(0.5\beta_j), \sin(0.5\alpha_j)\sin(0.5\beta_j)]^T.$$

Main cycle

1. Estimation of the reference camera CS current angular position by formulas (4), the corresponding to its position rotation matrix $R_{\phi0} = \begin{bmatrix} \cos \varphi & -\sin \varphi & 0 & 1 \\ \sin \varphi & \cos \varphi & 0 & 0 \\ 0 & 0 & \cos \theta & -\sin \theta \\ 0 & 0 & \sin \theta & \cos \theta \end{bmatrix}$ and the corresponding quaternion $q_{\phi0}$ by formulas (7) and (8).

2. Calculation of the quaternion $q_{vis}$ for a given angular position of the RoI center:

$$q_{vis} = [\cos(0.5\alpha)\cos(0.5\beta), \cos(0.5\alpha)\sin(0.5\beta), \sin(0.5\alpha)\cos(0.5\beta), \sin(0.5\alpha)\sin(0.5\beta)]^T,$$

where $\alpha$ and $\beta$ are the azimuth and elevation of the line of sight, and quaternions

$$q_{ov} = q_{vis} \cdot q_{uv0}$$

determine the direction of the radius vectors from the virtual unit sphere center to the RoI pixels $(u, v)$.

3. Filling of the $i$-th layer of RoI with pixels from cameras (taking into account the distortion of their lenses):

$$x_{uv} = \mathbf{P}_i \cdot \text{rot}(\mathbf{M}_{3D}, q_{\text{cam-IMU}} \cdot q_{\phi0}) / [\mathbf{P}_i \cdot \text{rot}(\mathbf{M}_{3D}, q_{\text{cam-IMU}} \cdot q_{\phi0})],$$

where $i$ is number of DPS camera and $\mathbf{P}_i$ is its projection matrix,
\[ M_{3D_{av}} = \mathbf{K}_\mathbf{v}[\mathbf{R} | \mathbf{t}] \],

\[ M_{3D_{av}} = \{ T_{LRM}[\hat{D}_{av} \mathbf{M}_{av}^T, 1]^T \}^{1\ldots3} \],

\[ T_{LRM} = \begin{bmatrix} \mathbf{R}_{LRM} & \mathbf{t}_{LRM} \\ 0 & 1 \end{bmatrix} \]

is the transformation matrix for the transition from LRM CS to CS of reference DPS camera, \( \mathbf{0} = [0, 0, 0]^T \), \( \mathbf{M}_{av} \) is the point of intersection of the virtual unit sphere and the radius vector from its center to the RoI pixel with the coordinates \((u, v)\):

\[ \mathbf{M}_{av} = [2(q_xq_z - q_y q_v), q_xq_z - q_y q_v, q_x^2 + q_z^2 - (q_x^2 + q_y^2)]^T \],

where \( q_x \) and \([q_x, q_y, q_z]^T \) are respectively vector and scalar parts of the \( \mathbf{q}_{av} \) quaternion, \( \hat{D}_{av} \) is the estimate of the distance to the object that forms the brightness of the \((u, v)\) RoI pixel \( \mathbf{O}_I \) with coordinates, and «(3)» and «\(<1\ldots3>\)» symbols mean respectively 3rd row of matrix and first 3 elements of vector. The operator \( \text{rot}(v_{av}, \mathbf{q}) \) in (10) means the rotation of the vector \( v_{av} \) by an angle determined by the quaternion \( \mathbf{q} \), represented by the Rodrigues – Hamilton parameters:

\[ \text{rot}(v_{av}, \mathbf{q}) \rightarrow [0, v_{av} \text{rot}^T]^T = \mathbf{q} \cdot [0, v_{av}^T]^T \cdot \mathbf{q}^* \].

The estimate of distance \( \hat{D}_{av} \) is obtained as the distance to the point where the straight line with the vector of direction cosines

\[ \mathbf{M}_{3D_{av}} = \mathbf{M}_{av} / || \mathbf{M}_{av} || \]

intersects the plane, passing through three points \( \mathbf{M}_k = D_k \text{rot}(0, 0, 1)^T \), \( \mathbf{q}_{LRM_k} \) with known ranges \( D_k, k \in [1, N_{LRM}] \), and the intersection point belongs to the triangle with vertices \( \mathbf{M}_k \). One of the effective algorithms of checking the belonging of a point to a triangle in three-dimensional space is the method of barycentric coordinates [21]. The points for constructing the plane are selected by the criterion of the minimum of the angle between the directions determined by the direct cosines vector \( \mathbf{M}_{3D_{av}} \) and the three vectors \( \mathbf{v}_{LRM_k} = \text{rot}([0, 0, 1]^T, \mathbf{q}_{LRM_k}) \). This criterion can be written as:

\[ \mathbf{M}_{3D_{av}} \mathbf{v}_{LRM_k} \rightarrow \max \],

where «\(\cdot\)» is a dot product.

4. Performing the procedure for correction of brightness differences (blending) [22] in different layers, corresponding to the same spectral range.

If necessary, the dynamic change of the field of view of the RoI recalculation of quaternions \( \mathbf{q}_{av0} \) is performed in the body of the main loop [19].

As the processing according to the above algorithm is homogeneous for each pixel of the RoI, this allows us to apply the procedure of parallelization of calculations [23, 24], for example, using GPU resources.

In a number of applications, for example, during a low-altitude flight of a manned aircraft (MA), in which the DPS is a survey optical-electronic system, it is necessary to take into account that the foreshortening of the scene observed from the location of the pilot’s head (LoPH) in the aircraft may vary. With the known translation vector for the transition from the LoPH to the principal point of the reference camera, it must be additionally taken into account while the projection matrices \( \mathbf{P}_i \) (11) are being calculated. If the axes of the reference camera CS are parallel to the construction axes of the aircraft, then

\[ \mathbf{P}_i = \mathbf{K}_\mathbf{v}[\mathbf{R}_i | (\mathbf{t}_i + \mathbf{t}_{LoPH})], i = 1, 2, \ldots, N_{cam}. \]

This approach is equivalent to the forming of RoI as an image from a virtual camera, the main point of which coincides with the LoPH, not with the principal point of the DPS reference camera.

6. Experimental results

Experimental results were obtained on a DPS layout, which construction is described in [19, 20]. The DPS layout cameras and based on the debugging board with the MEMS MPU-9150 sensor IMU were pre-calibrated according to the methods discussed in paragraphs 2-4.

A semi-natural experiment on the forming of a video panorama was put as follows: using a Leica Disto D2 LRM measurements of the distances \( D_j \) from the end of the reference camera lens to the
reference points were performed (these reference points are the window opening angles of the nearest buildings and the lower edges and skates of their roofs, (figure 6); the position of reference points was controlled by a telephoto lens. For these points the corresponding pixels in the image of the auxiliary camera were manually found and the angular directions \((\alpha_j, \beta_j)\) for the reference camera were obtained. We also made the assumption that \(\mathbf{R}_{LRM} = \mathbf{E}\) and \(\mathbf{t}_{LRM} = [0, 0, 0]^T\), where \(\mathbf{E}\) is an identity \(3\times3\) matrix. For pixels \((u, v)\) of RoI to which the estimates of distance were not calculated were assigned the points of space with \(\|\mathbf{M}_{uv}\| = 10\) km (thus infinity was simulated).

Figure 6 shows the results of fusion from three TV cameras in RoI, taking into account the ranging information (blending mode is disabled for clarity). Analysis of the image areas in the RoI at a scale of 800% allows us to conclude that the absolute registration error is achieved for almost the entire RoI field of no more than 1 pixel.

For RoI with \(W \times H = 1024 \times 768\) and \(\Delta \varphi_w \times \Delta \varphi_h = 40^\circ \times 30^\circ\) this value corresponds to an angular error of about 2.6′ (i.e. even with preliminary calibration, the registration error that has been reached by the authors, approximately 3 times more than the resolution of the human eye). The same error value is also valid for superimposition the RoI layers from both the TV and the LWIR channels (figure 7).

In sectors of OI, for which there are no estimates of range, the assumption that all scene objects are in infinity results in absolute superimposition errors in the near zone (up to 100 meters) up to 8-10 pixels (in the left part of figure 8 along the border of the center and left bottom frame stitching). With the above RoI parameters these errors correspond to angular errors up to 20-25′.

Figures 9 and 10 show the change in foreshortening when the LoPH is displaced from the main point of the DPS reference camera at 2 meters higher and 2 meters back when \(\Delta \varphi_w \times \Delta \varphi_h = 60^\circ \times 45^\circ\) (blending mode is on). According to the subjective sensations of the authors, who visually observed
objects in the near zone from the LoPH, the RoI of figure 9 is closer to the subjective perception of height above the shooting surface than the RoI of figure 10 (for example, the image of the building on the right side of the RoI).

Figure 9. The result of the RoI forming taking into account the information on the relative position of the LoPH and the DPS reference camera at $t_{\text{LoPH}} = [0, 2, 2]^T$; matrices $P_i$ are calculated by (12).

Figure 10. The result of the RoI forming without taking into account the information on the relative position of the LoPH and the DPS reference camera; matrices $P_i$ are calculated by (11).

7. Conclusion

The preliminary calibration of cameras and auxiliary sensors of the DPS system in the presence of information about the distances to the objects of the scene made it possible to ensure an absolute angular error of alignment in the region of interest of no more than three angular minutes. Virtual region of interest mode, which takes into account the observer offset relative to the DPS reference camera, allows us to create images from a foreshortening corresponding to the subjective visual perception.

Appendix A

Since all quaternions in (6) are unit quaternions, $||q|| = 1$, then the quaternion, the inverse of $q$, will be complexly conjugated with it: $q^{-1} = q^*$. Express the quaternion $q_{\text{cam-IMU}}$ from (6). To do this multiply both sides of (6) on the left by $q_{\text{IMU}}^*$ and on the right – by $(q_{\text{cam}} \ast q_{\text{IMU}})^{-1} = q_{\text{TO}}^{-1} \ast (q_{\text{cam}}^{-1})^{-1} = q_{\text{TO}}^{-1} \ast q_{\text{cam}}^{-1}$. We represent the product of quaternions in the right side of (A.1) as the product of the matrix $Q_{\text{IMU}}$ composed of $q_{\text{IMU}}^*$ elements according to (9), and the quaternions $q_{\text{cam-IMU}}$ and $q_{\text{TO}}^{-1} \ast q_{\text{cam}}^{-1}$ in the form of the corresponding to this quaternions four-element vectors $v_{\text{cam-IMU}}$ and $v_{\text{cam}}$:

$$Q_{\text{IMU}} v_{\text{cam-IMU}} = v_{\text{cam}}.$$  (A.2)

In system (A.2) the number of equations is equal to the number of unknowns, therefore, if the matrix $Q_{\text{IMU}}$ is non-degenerate, then

$$v_{\text{cam-IMU}} = Q_{\text{IMU}}^{-1} v_{\text{cam}}.$$  (A.3)

Since in each $m$-th calibration the angular positions of TO, the angular position of the camera relative to TO and IMU angular position are estimated with an error, then not each of $m = 1...M$ equations (6), but the overdetermined system of equations for all $M$ positions should be solved:

$$Q_{\text{IMU}} v_{\text{cam-IMU}} = v,$$  (A.4)

where the $Q_{\text{IMU}}$ matrix is obtained by stacking the $Q_{\text{IMU}}$ matrices and $v = [v_1^T, v_2^T, ... , v_M^T]^T$. Pseudosolution of (A.4) is a vector:

$$v_{\text{cam-IMU}} = Q_{\text{IMU}}^+ v,$$

where $Q_{\text{IMU}}^+ = (Q_{\text{IMU}}^T Q_{\text{IMU}})^{-1} Q_{\text{IMU}}^T$ is a pseudoinverse Moore – Penrose matrix.
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