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Analysis on the dynamic deformations of the images from digital film sequences

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Abstract: Image sequences, in particular digital video sequences, are characterised by the features which result in their high potential as measurement data. However, as early as at the stage of visual assessment of digital film images, originating, in particular, from amateur cameras, occurrence of some deformations may be observed, which may highly influence the results of measurements performed using these images; such deformations differ from deformations occurred in the case of static photographic images. It results both, by the method of image recording, using an electronic shutter and interlaced or progressive scanning, as well as the method of file recording and compression. It is worth to notice the systematic nature of such deformations, which highly depend on mutual motions of a camera and recorded objects. The objective of presented research works was to develop the mathematical description of image deformations, as a function of motion parameters. This would allow for adaptation of the camera calibration process to the demands of sequential imaging, as well as for modification of algorithms of measurements using self-calibration, and, as a result, minimisation of deformations. Another objective was to analyse the influence of deformations, typical for digital film images, on the results of measurements performed using these images, by means of series of experiments, which were based on multiple calibration of static and a moving camera, also with the use of a spatial test field. The first part was made by developing formulas based on some geometric relations, using some simplifications. On the stage of experimental research a certain degree of compatibility of experimental results and theoretical assumptions were confirmed.

Keyords: image sequences, digital video camera, internal geometry, non-metric camera, camera calibration

1. Introduction

Issues related to utilisation of image sequences have been the subject of growing interest of experts from many scientific sectors and disciplines. Besides photogrammetry and remote sensing, they also include IT, optical electronics, optical metrology, computer vision, virtual reality technology or, indirectly, transport, robotics, architecture, archaeology, medicine and even sport and astronautics. This results from the common and permanently growing accessibility of recording devices and the specific features of image sequences, which result in their high measuring potential.

As examples of applications of image sequences, biological and natural research works may be mentioned, which concern analyses of motions of glaciers (Maas et al., 2006) or investigations of variations of surfaces of water reservoirs (Santel et al., 2004). Another important group consists of measurements and tests of motions of human bodies, which are applied in medicine, and, in particular in orthopaedics (Wardzińska, 2007) and sports medicine (Fua et al., 2000; Pullen, 2002) or in the virtual reality techniques. More applications may be mentioned, such as those which are related to the wide transport issues, including traffic and pedestrian motion analyses (Spangenberg and Döring, 2006), measurements performed for the needs of technical inspection of vehicles (Trzeciak, 2010) or „intelligent vehicles" which are becoming more popular; they are equipped with driving assistance systems, allowing for automatic braking in emergency situations, tracking of motions along road lanes, parking assistance or even automatic driving (Franke and Gehrig, 2013). While mentioning these topics, it is also worth to notice the successive application of visual sequences, which is visual navigation and control of various types of vehicles and robots (Sim et al., 2002). As the last, but not least, group of applications, 3D modelling, which is based on image sequences, should be mentioned. The list of objects, which are 3D modelled includes architectural monuments (Reznicek and Pavelka, 2008), human bodies, as well as various types of engineering structures. Cameras which record image sequences may be used independently or as a part of a bigger set of instruments (as it happens in MMS (Mobile Mapping Systems or Multisensoral Mapping Systems)) (Gandolfi et al., 2008; Hunter, 2009).

Such wide range of possible applications of sequential analysis results from their characteristic features, which may be considered as advantages or disadvantages, having considerable influence on the quality of results of works. Due to this the necessity of their detailed analysis appears, which should be performer in order to facilitate forecasting of available accuracy or, to increase it by means of modifications of algorithms of measurements.

2. Characteristics of image sequences

The best starting point for the discussion of characteristics of image sequences is the dictionary definition of the word "sequence"; it says that it is "a set of related events, movements, or items that follow each other in a particular order" (Oxford Dictionaries, 2014). It is clear that the terms "image sequences", "sequential images" or "visual sequences" are used in relation to such sets of images for which this sequential ordering is important with respect to considered, possible applications. Additional important factor, which contributes to the term "image sequences" is the determined, and uniform (if possible), and relatively high frequency of recording of particular images. As an example of a image sequence a set of particular frames selected from a film, should be mentioned.

3. Internal geometry of images

The term "internal geometry" of an image is understood as the shape of a bundle of perspective rays which create the image. Due to this, the internal geometry consists both, of the basic elements of internal orientation, such as coordinates of the principal point and the focal length, as well as the distribution of various deformations, including the basic lens imperfections – chromatic aberration, spherical aberration, coma, astigmatism, field curvature and distortion (which is very important from the photogrammetric perspective) (Kurczyński, 2006). Besides, depending on the applied method of image recording, other parameters should be also considered; they include deformation of photographic background and film non-adherence (in the case of analogue photographs) (Linsenbarth, 1974; Markowski, 2010) or the influence of the method of recording of digital images (in particular, film images, which are discussed in this paper).

Geometric image deformations may be mathematically described in the high accuracy; when parameters, which determine those deformations are known, their influence on results of work may be eliminated. Those parameters may be determined independently from measurements of analysed objects, at the stage of camera calibration or adjustment of observations of a measured object, by introducing additional terms to observational equations. At this time it should be stressed that the most important feature of a measuring camera, which influence the accuracy of results, are not the minimum values of geometric deviations from an ideal central projection (since this influence may be minimised using the previously discussed models), but it is the stability of discussed deformations, which highly influences the possibility to determine the values of parameters, which describe those deformations.

4. Image deformations typical for digital film images

As it was mentioned in section 2, film images – besides the discussed, standard geometric parameters, resulting from specific features of the optical system, including the imperfections of a lens – are also characterised by features resulting from the way of image acquisition and recording in the device memory.

4.1. Interlaced and progressive image scanning

The basic difference between digital film images and standard photographs is the lack of the mechanic shutter and line by line recording (scanning) of the image. Two types of image recording: the interlaced and progressive scanning may be mentioned.

The interlaced method consists of recording of only every second image line and then complementing it with every second line from the successive frame. As a result, one resulting image contains two recorded images, which are characterised by two times lower, vertical resolution (Fig. 1). When such images are reproduced, in order to eliminate the "comb" effect, the half-images are averaged or missing lines are amended by means of interpolation (Markowski, 2012)

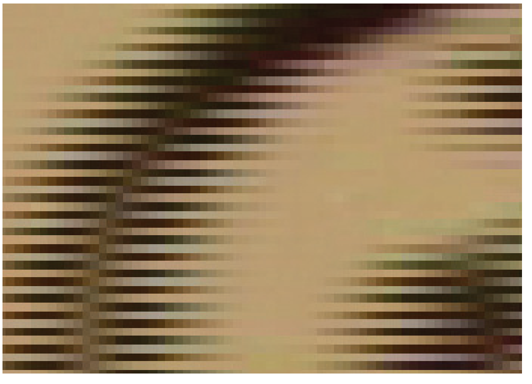


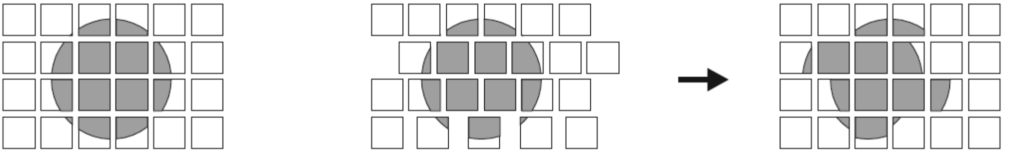
Fig. 1. An example of interlaced image scanning

Progressive scanning is the opposition to interlaced scanning; in the case of progressive scanning full film frames are recorded, line by line. As a result information loss from every second image line does not occur, there is no need of deinterlacing with the use of above mentioned methods.

4.2. Image deformations resulting from non-simultaneous recording of particular lines

The image recording method, which is typical for digital film images, is often connected with the appearance of a specific type of deformations, which may be determined as dynamic deformations, similarly to the geometry of images generated by electro-optical scanners. They are the result of mutual motions of a camera and observed objects at the time of image scanning. As a result, diversified image positions are recorded, since each line is recorded at another moment.

The type of deformations may be highly diversified, since it is connected with mutual motions of a camera and observed objects; therefore it is influenced by such factors as linear and angular velocities in particular directions, or distances between a camera and objects. Movements which are in agreement with the scanning direction result in a quite different type of deformations than in the case when these motions are mutually perpendicular, parallel or orthogonal to the image plane; they are also different in the case of rotations.



a.

b.

Fig. 2. A diagram explaining principles of generation of dynamic deformations (a) (Kraus et al., 2007) and example of an image with deformations (b) (Kowalczyk, 2012)

When comparing images acquired with the use of interlaced and progressive scanning with respect to dynamic deformations, it may be noticed that deformations are much higher in the second case. It results from the time of recording, since in the case of interlaced images it is necessary to record only a half of lines, what results in highly shortening the time of single field (half-image) registration, so that there is a smaller displacement during the registration.

4.3. Image recording and compression

Another difficulty which is experienced in the case of digital visual sequences is the issue of image compression. To the contrary of static digital photographs, besides intra-frame compression, also inter-frame compression is often applied in the case of film recording. In this method the film is divided into three types of frames: I – only intra-frame coding, e.g. similarly to the JPEG standard, P – coding with the use of one-direction prediction basing on preceding frames, and B – coding with the use of two-direction prediction by means, in a sense, of interpolation from preceding and following frames (Fig. 3). This type of compression is used in such formats as MPEG-2, or MPEG-4. Additionally, contemporary codecs also utilise the motion compensation, what allows to achieve the higher effectiveness of compression of films which presents moving objects. However, the format of recording film sequences, determined as M-JPEG, still exists and is utilised in some cameras; this format utilises only the intra-frame compression and thus such a film may be considered as the sequence of images in a format similar to JPEG (Domański, 2010; Nasiłowski, 2004).

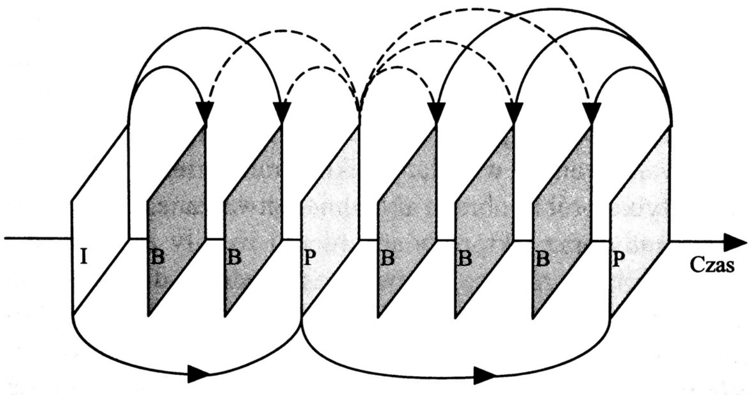


Fig. 3. A diagram of inter-frame compression (Domański, 2010)

It has not been defined how the measuring potential is influenced by utilisation inter-image compression and motion compensation. It also seems that the influence of these factors on image geometry is far less systematic and predictable than in the case of dynamic deformations. That is why this aspect was not taken into consideration in discussed experiments; the recording device supporting the M-JPEG was utilised in the experimental part of works.

5. An attempt to mathematically describe dynamic deformations

Similarly to other image deformations, dynamic deformations may highly influence the accuracy of measurements. However, similarly to the case of optical distortion or deformation of analogue photographic background, it seems that it is possible to minimise this influence using appropriate corrections to observations or introducing geometric corrections of images. In order to perform this, it is necessary to know their mathematical description. Initially it could be assumed that models applied for mathematical description of conventional photographic images, such as Ebner of Brown models, may be successfully applied also in the discussed case. However, a serious problem appears, which is the instability in time of dynamic deformations; which results in possibly different deformations of practically each photograph in a sequence.

It turns out however, that in the case of dynamic deformations one of their features is regularity, concerning dependence of their values from parameters of mutual motions of a camera and objects. Therefore it is possible to model image deformations depending on the mentioned values, such as linear and angular velocities in particular directions. It's worth to notice that this solution seems to be quite innovative, because so far the issue of dynamic deformations of the images from digital film sequences was signalized in the literature (Kowalczyk, 2012; Kraus et al., 2007) but quite as an imperfection of digital video images. However, it is highly difficult to find some examples of the solution to this problem through the geometric corrections of images or applying some corrections to observations.

5.1. Digital film images versus conventional photographs and electro-optical scanners

As it was mentioned, the geometry of digital film images is characterised both, by the features of conventional frames, as well as images acquired by means of electro-optical scanners. However, the final recording of a film is more complicated than in the first or the second case. Image scanning is performed within a frame and, when it is completed, recording of the successive frame begins. Besides, the motion of a recorded line is not the result of the motion of entire camera, but from variations of the recorded part of the image. Therefore the internal geometry of each line results from the geometry of a given part of the optical system; it is not permanent, as it takes place in the case of an electro-optical scanner. Each line *de facto* has different outer orientation, what is similar, in turn, to the case of a scanner. At the stage of processing of observations it is not possible to directly utilise this similarity, looking at each line as a separate "image", since this would highly complicate measurements, due to the high volume to be processed and demands for development a new algorithm of measurements. It seems that the more efficient solution would be to process images to such a form which would allow to process them as conventional, static photographs. Geometric corrections or consideration of appropriate corrections of observations may be used for that purpose.

5.2. Influence of particular parameters of motions on image geometry

As it was mentioned, the type of dynamic deformations depends on the direction and type of mutual motions of a camera and objects. Since the motion, which took place in a time unit, corresponding to recording of an image line, is important, the best parameters of motions, which should be considered, are linear and angular velocities. In order to simplify, in presented discussion only the case when the camera is moving in relation to a stationary object will be considered and the description of the motion will be decomposed into components of the linear velocity along the axes of a spatial coordinate system of image and the related angular velocity, following the standard, Euler's definition of angles, used in photogrammetry.

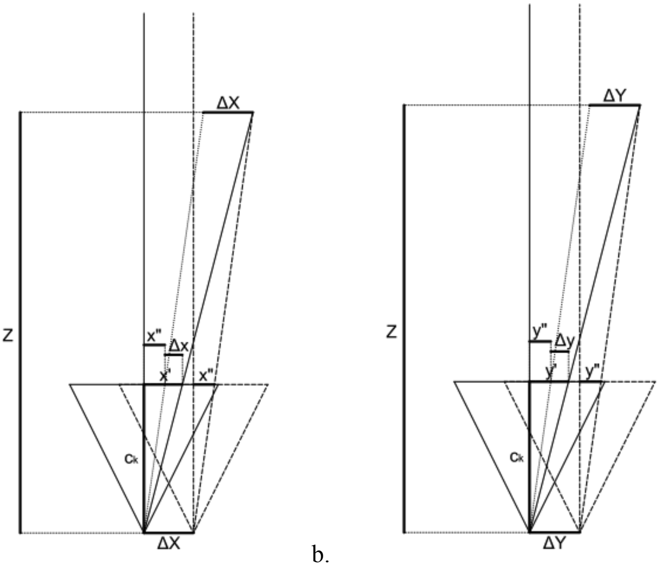


Fig. 4. Geometric relations used for developing formulas describing dynamic deformations caused by the progressive camera motion with the direction of the x axis (a.) and y axis (b.)

Deformations caused by the progressive camera motion, in agreement with the directions of lines of scanning seem to be the easiest for description, since as a result of such motion only mutual horizontal shift of particular image lines (Fig. 9.a) occur. The value of this shift may be determined from the formula (1), which was developed from appropriate geometric relations (Fig. 4.a).

$$\Delta x = s \cdot y'_{[pix]} \cdot V_X \cdot t_l \cdot \frac{c_k}{Z}$$
$$\Delta y = 0 \qquad (1)$$

where: Δx, Δy – shift of a given pixel, s – sign ($s \in \{-1;1\}$ depending on the scanning direction), $y'_{[pix]}$ – y image coordinate (or the line number) in pixels, V_x – velocity in the direction of x axis, t_l – time of the line recording, c_k – the focal length, Z – the distance from a measured object.

Similar shifts occur in the case of motion, which is parallel to the photograph plane, but in the direction orthogonal to lines of scanning (2) (Fig. 4.b). However, they result in different deformations due to the fact that they occur in the direction of growing of the number of lines of scanning, and not in the orthogonal direction, as in the previous case (Fig. 9.b).

$$\Delta x = 0$$
$$\Delta y = s \cdot y'_{[pix]} \cdot V_Y \cdot t_l \cdot \frac{c_k}{Z} \tag{2}$$

where: V_y – velocity in the direction of y axis, other symbols are the same as in formula (1).

A little different shifts of image points occur in the case of motion, which is orthogonal to its surface (3) (Fig. 5). This is connected with the scale variations for particular lines, what results in shifts in directions of the x and y axes (Fig. 9.c).

$$\Delta x = s \cdot y'_{[pix]} \cdot \frac{x' \cdot V_Z \cdot t_l}{Z + V_Z \cdot t_l}$$
$$\Delta y = s \cdot y'_{[pix]} \cdot \frac{y' \cdot V_Z \cdot t_l}{Z + V_Z \cdot t_l} \tag{3}$$

where: V_z – velocity in the direction of z axis, other symbols are the same as in formula (1).

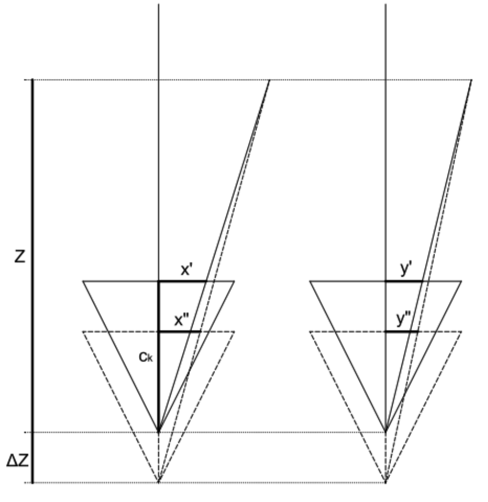


Fig. 5. Geometric relations used for developing formulas describing dynamic deformations caused by the progressive camera motion with the direction of the z axis

More complicated formulae must be used to describe deformations, which are caused by the camera rotation around the axes, which are marked according to the standards of Euler's angles notation, as ω, φ, κ . Thus, for rotation around the x axis (ω) (Fig. 9.d), shifts in both directions may be expressed by the formulae (4) (Fig. 6).

$$\Delta x = s \cdot y'_{[pix]} \cdot \frac{x'}{c_k}\left(y' + s \cdot \frac{y' + c_k \cdot \tan(\omega_\omega \cdot t_l)}{1 + \frac{y'}{c_k} \cdot \tan(\omega_\omega \cdot t_l)} \cdot y'_{[pix]} - \frac{c_k \cdot \tan(\omega_\omega \cdot t_l)}{Z} \right) \cdot \sin(\omega_\omega \cdot t_l)$$

$$\Delta y = s \cdot y'_{[pix]} \cdot \frac{y' + c_k \cdot \tan(\omega_\omega \cdot t_l)}{1 + \frac{y'}{c_k} \cdot \tan(\omega_\omega \cdot t_l)} \tag{4}$$

where: ω_ω – angular velocity around the x axis, other symbols are the same as in formula (1).

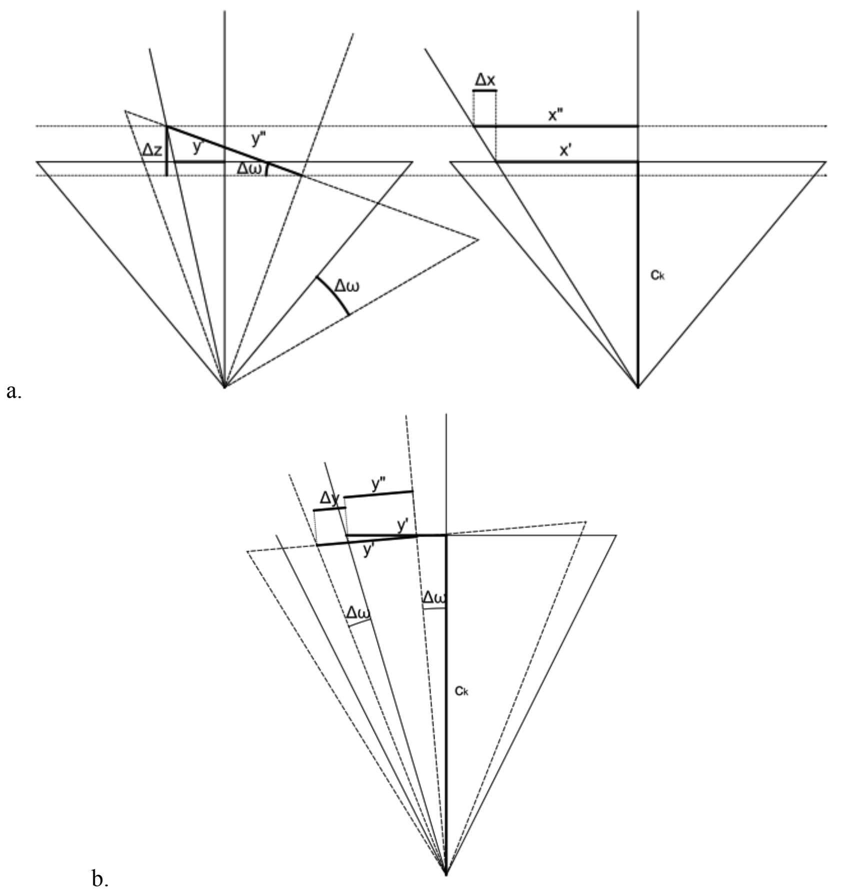
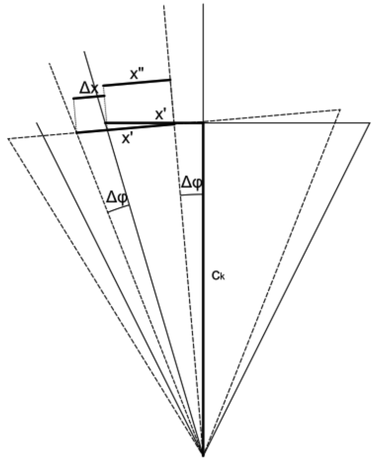
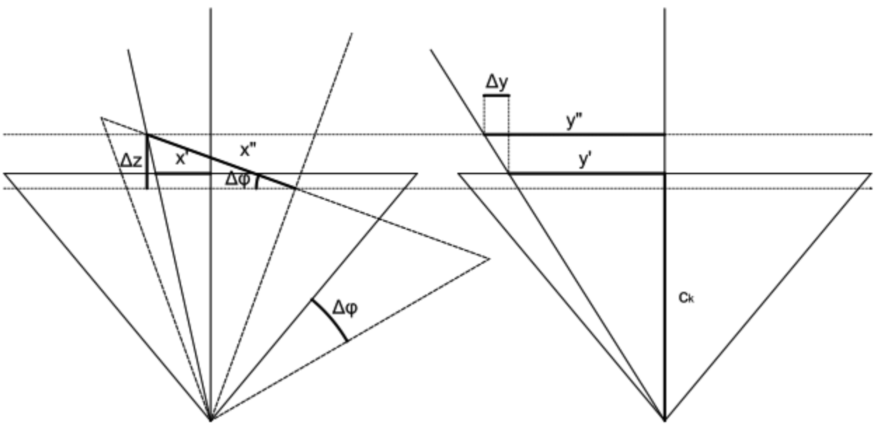


Fig. 6. Geometric relations used for developing formulas describing dynamic deformations (a. – with the direction of the x axis, b. – with the direction of the y axis) caused by the camera rotation around the x axis



a.



b.

Fig. 7. Geometric relations used for developing formulas describing dynamic deformations (a. – with the direction of the x axis, b. – with the direction of the y axis) caused by the camera rotation around the y axis

Similarly to the case of the progressive motion in directions of the x and y axes, descriptions of shifts around the y axis are analogueous to descriptions around the x axis (5) (Fig. 7); however, due to the change of direction they result in different image deformations (Fig. 9.e).

$$\Delta x = s \cdot y'_{[pix]} \cdot \frac{x' + c_k \cdot \tan(\omega_\varphi \cdot t_l)}{1 + \frac{x'}{c_k} \cdot \tan(\omega_\varphi \cdot t_l)}$$

$$\Delta y = s \cdot y'_{[pix]} \cdot \frac{y'}{c_k} \cdot \left(x' + s \cdot \frac{x' + c_k \cdot \tan(\omega_\varphi \cdot t_l)}{1 + \frac{x'}{c_k} \cdot \tan(\omega_\varphi \cdot t_l)} \cdot y'_{[pix]} - \frac{c_k \cdot \tan(\omega_\varphi \cdot t_l)}{Z} \right) \cdot \sin(\omega_\varphi \cdot t_l) \quad (5)$$

where: ω_φ – angular velocity around the y axis, other symbols are the same as in formula (1).

Another situation occurs in the case of rotation around the z axis, since for particular lines a simple rotation around the principal point occurs (Fig. 8), which may be described by formulae, which are commonly applied for transformation of coordinates; the only difference concerns the dependence on time and the order of scanning (6) (Fig. 9.f).

$$\Delta x = s \cdot y'_{[pix]} \cdot (x' \cdot \cos(-\omega_\kappa \cdot t_l) - y' \cdot \sin(-\omega_\kappa \cdot t_l) - x')$$
$$\Delta y = s \cdot y'_{[pix]} \cdot (x' \cdot \sin(-\omega_\kappa \cdot t_l) + y' \cdot \cos(-\omega_\kappa \cdot t_l) - y') \quad (6)$$

where:, ω_κ – angular velocity around the y axis, other symbols are the same as in formula (1).

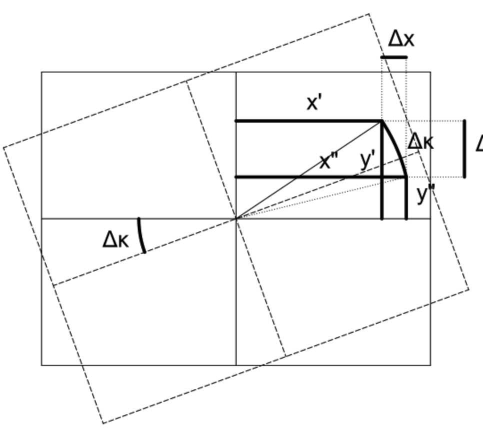


Fig. 8. Geometric relations used for developing formulas describing dynamic deformations caused by the camera rotation around the z axis

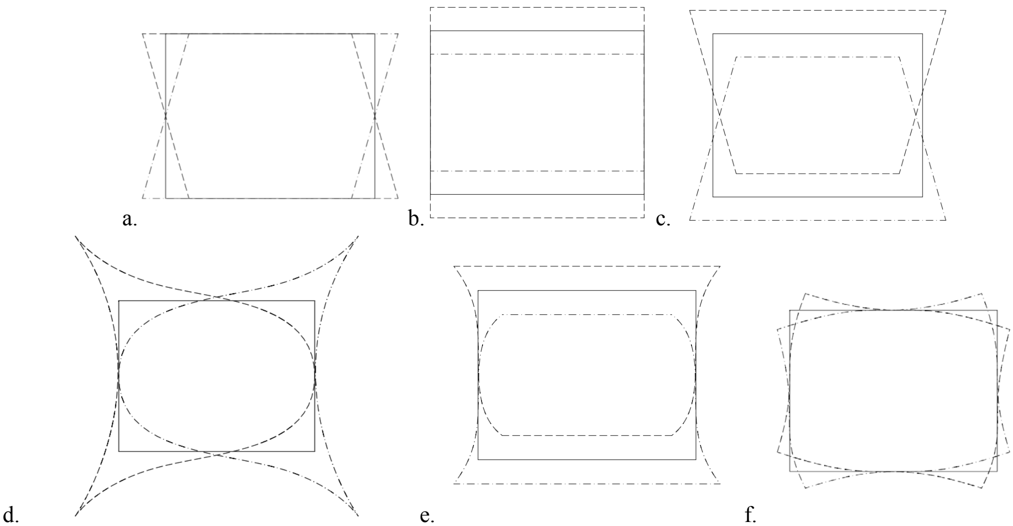


Fig. 9. Probable distribution of dynamic deformations resulting from the influence of particular components of progressive (a.-c.) and rotating (d.-f.) motions

It is worth to note that presented formulae are somehow simplified. The first simplification concerns negligence of the issue of the order of recording and resulting lack of the possibility to shift points of the successive image line onto the already recorded line. The second simplification is the assumption of stability of motion parameters during recording of a given frame, although they may vary, what would result in diversification of dynamic deformations for particular image lines. In order to consider those two aspects, instead of estimation of deformations in dependence of image coordinates, their values should be separately determined for each image line, basing on deformations of the preceding line. The decision concerning the selection of a better solution should be made within further investigations of the discussed issues.

6. Experimental research on image internal geometry

Besides theoretical considerations aiming at development of formulae, which describe the distribution of dynamic deformations, experiments which were to compare forecasted values with observed, real deformations, by means of multiple calibration of recorded images by the moving camera.

6.1. The scope of performed experiments

Nikon D5000 was the digital reflex camera used for experiments; it allowed for taking standard photographic images and recording films in M-JPEG standard, in the HD resolution of 720p (1280x720 pixels, with progressive scanning). A simple zoom lens, AF-S DX Nikkor 18-55 mm f/3.5-5.6G VR was applied, which is sold as a kit lens together with the camera.

The element which was important from the perspective of discussed experiments, was such camera mounting, which allowed to perform the motion, corresponding to a single component of its description (progressive motion along the direction of one of the axes or the rotating motion around the axis) during single recording. Investigations concerning the influence of progressive motion on image deformations seemed to be problematic due to the necessity of utilisation of a special cart on which the camera would move along straight lines, in directions following the directions of the axes of the coordinate system. At this time it is very important that observable vibrations of this motion should be eliminated, what turned to be difficult in practice. Due to this it was decided to analyse the influence of the camera rotation of image deformations and to plan the experiments concerning the progressive motion as topics of the future research works.

The camera rotating motion was performed by placing the camera on a relatively heavy and stable Manfrotto tripod, equipped with a three-axis 3D head and film recording during the camera motion in one of the directions, when other directions were blocked by tightening appropriate clips of the tripod head. The influence of eccentric camera mounting was neglected, as it was considered as small. The spatial test field was the subject of recording; it consisted of 52 points with coordinates measured with the use of a coordinate measuring machine; the points were positioned on cylindrical cotter-pins, fixed to the massive, metal plate (Fig. 10). The lens focal value was set to the shortest range, i.e. 18 mm (27 mm for the 35 mm standard). Parameters such as aperture or the exposure time, were automatically set by the camera, since it was noticed, at the stage of previous experiments (Markowski, 2012), that manual settings are highly limited in the case of film recording (real parameters turn to be different than set values). Focusing the lens for the distance from the object was set once using the *autofocus* function; it was turned off in order to keep the unchanged focusing for all sequences.

In order to distinguish particular frames from film sequences and to record them in the form of separate graphic files the author's function of Matlab tool was used; it was developed within the frames of previous works on utilisation of image sequences for measuring purposes (Markowski, 2012; 2013). It was decided to record every twelfth frame; this resulted from the camera imaging frequency (for recording 24 frames per second the resulting images were recorded every 0.5 sec.).

The next step concerned manual measurements of image coordinates of points; they were performed using the P.exe application, performed for all images distinguished out of 6 sequences: 2 sequences for each component of the angular motion and single images from each of 4 reference sequences, recorded by the fixed camera.

All results of measurements were processed with the use of Kalib.exe software; as a result internal orientation elements were obtained (expressed in pixels) and outer orientation elements in the system of the test field. Applying the another author's function of the Matlab environment, developed in the frames of previous works (Markowski, 2012; 2013), parameters of the camera motion in relation to the test field, were determined basing on the camera outer orientation elements.

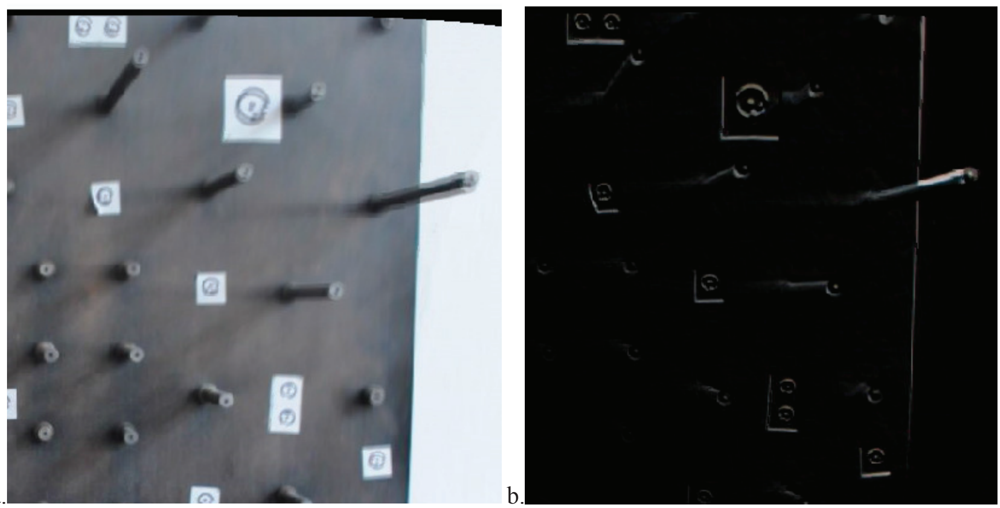
Fig. 10. Recording of films used for research on the internal image geometry

Those images, for which the centre of the test field was recorded within the shortest distance from the frame centre, were selected for further analyses, from recorded images and using their internal orientation elements. Thus sets of points measured in similar locations on photographs were used for the needs of comparing; at the same time images falling at the centre of the course of a given motion were utilised, what was considered as important due to minimisation of occurrence of errors, which disturbed the results of performed analyses.

Using the specially prepared, author's function of the Matlab environment, geometric corrections of particular, selected images were performed, basing on parameters, previously determined for those images, which described deformations (radial distortion, tangential distortion and affine deformations). Additionally, diagrams of distribution of deformations and images resulting from overlapping and subtracting images before and after corrections, were generated in order to simplify their analysis.

In order to analyse distribution of deformations, which are influenced by the motion, geometric correction of all selected images was also performed, using the data concerning deformations, acquired from calibration based on the first of reference images (acquired by the fixed camera). This allowed for minimisation of the influence of stable geometric parameters and considering only deformations caused by geometric instability, including dynamic deformations.

The next step concerned new measurements of image coordinates using the P application and calibration using the Kalib software, for both sets of images, geometrically corrected. Then, for the needs of research works, geometric corrections were introduced again, basing on deformations remaining after previous corrections; diagrams of their distribution were also generated, as well as images resulting from overlapping (averaging) and determination of differences of images after the single and double correction (Fig. 11).



a. b.

Fig. 11. Fragments of sample images resulting from overlapping (a.) and subtracting (b.) images after correction of deformations basing on calibration of the first (static) image and after additional correction of other deformations

6.2. Results of performed experiments

The objective of performed experiments was to test the influence of image dynamic deformations on the accuracy of measurements, performed on the basis of those images, depending on the motion of the recording camera. This objective had been met by selecting distributions of discussed deformations from total image deformations (which also included distortion and affine deformations), recorded at the time of rotating the camera around particular axes of the coordinate system (Fig. 12). For the needs of comparing similar works were performed, introducing geometric correction, every time on the basis of calibration performed using measurements from a given image (Fig. 13).

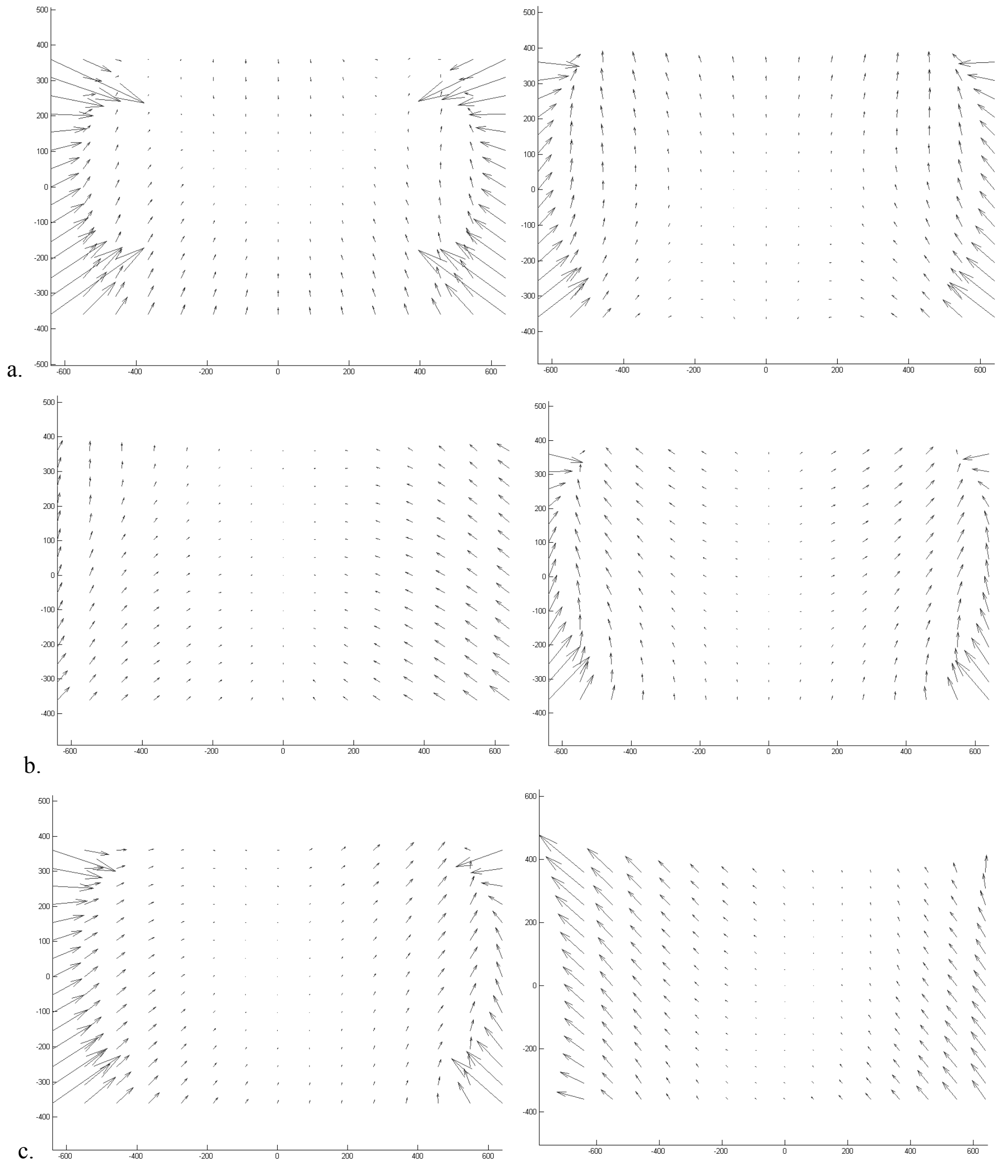


Fig. 12. Diagrams presenting distribution of dynamic deformations, determined as deformations of images recorded during rotation around x (a.), y (b.) and z (c.) axes, remaining after geometric correction introduced basing on parameters of deformations of the static reference image (5-time re-scaling of deformation vectors with respect to their distribution)

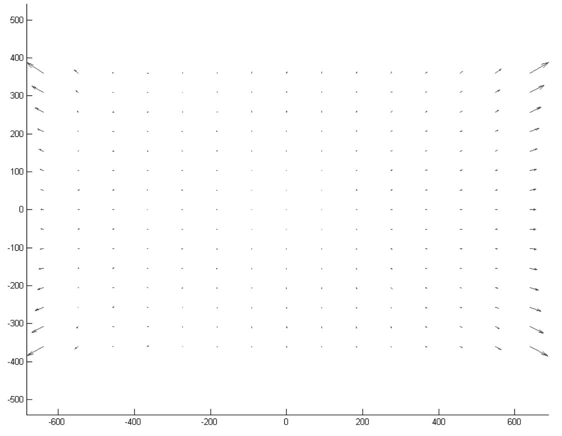


Fig. 13. An example of a diagram presenting distribution of deformations remaining after introduction of geometric correction based on calibration of the same image on which the correction were performed later (5-time re-scaling of deformation vectors with respect to their distribution)

According to previous expectations, diagrams which present distribution of deformations, which remain after geometric correction, based on calibration, independently for a given image (Fig. 13), proved vestigial (often subpixel) values of deformations. This confirmed the high calibration accuracy and correct implementation of geometric corrections. Both, in this case, as well as in diagrams of dynamic deformations (Fig. 12), one should not be suggested by deformations estimated for the image edges, since they were extrapolated considering that the test field covered only the central part of the frame. Such a procedure was accepted due to the relatively small number of test field's points.

When analysing diagrams of dynamic deformations of images (Fig. 12) and images of differences before and after corrections of other deformations, it may be noticed that – in the case of relatively slow motions (with the determined average velocity about 7-10º/s) – the existing deformations are relatively small and they reach the value of several pixels, as the maximum. However, it may be expected that in the case of higher angular velocity their influence will also be higher. However, in the case of cameras, such as the camera used for discussed experiments, additional phenomenon occurs, visible as the relatively high image blur, resulting from the lack of the possibility of manual settings of the exposure time and its adaptation to the motion velocity; as a result it is impossible to record good quality films using the camera moving with the high speed. Relations between the level of the image blur and dynamic deformations should be considered within the further investigations concerning the discussed topics.

It is worth to notice that the diagrams of deformations remaining after correction (Fig. 12), to some extent present the similarity to corresponding distributions of dynamic deformation values, which were initially assumed (Fig. 9). Appearing discrepancies may result both, from some inaccuracy of measurements, instability of conventional elements of the internal orientation, which describe the camera optical system, and from the applied at this stage, incorrect model of deformations, adapted to the description of distortion and affine deformations of photographs, and not to dynamic film deformations.

Unfortunately, at the present stage of works it was problematic to compare obtained values with particular results of calculations, based on the developed formulae. It was caused by the occurrence of the value of time of recording of a single image line, being the unknown feature of a given camera. Estimation of this value, as the unknown variable, introduced to the system of observational equations, is foreseen as one of the subjects of the future research works concerning the internal geometry of digital film images.

7. Final remarks and conclusions

Within the discussed experiments the issues related to internal geometry of digital film images were reviewed. It was noticed, that besides deformations typical for photography, resulting from imperfections of optical systems, also dynamic deformations occur, originating from specific methods of recording of images, which depend on linear and angular motion parameters. The objective which was met within the project was to prove that deformations might be described as functions of image coordinates, linear or angular velocity, time of recording of individual image lines, the focal length and the distance between the object and the camera. Within the project the attempt was also made to introduce formulae, which would describe those relations. The experimental part covered the analysis of distribution of dynamic deformations for several example sequences, recorded in the course of rotation of the camera around particular axes of the coordinate system.

In the course of analysis of results of experiments, certain compliance between real and forecasted deformations, theoretically considered, was confirmed. It was also noticed that for relatively slow camera motions, existing deformations have relative small values. Therefore, within the future research works concerning dynamic deformations of digital film images, limit values should be considered, for which it would be justified to take into account the influence of discussed deformations in measurement algorithms.

Some other aspects appeared in the course of discussed experiments; they should become the topics of the future considerations, which may include the issues concerning the order of recording of particular lines and the variability of motion parameters within a particular film frame. Their considerations require developed methods of correction of deformations, development of a method of determination of the recording time of particular lines, or investigations of relations between dynamic deformations and image blur and implementation of tests of deformations resulting from progressive motion.

As a part of further research on the internal geometry of digital image sequences, the probable influence of applied image compression method, especially inter-image compression and motion compensation should be noted. Another issue, worth to pay attention on it, is the usage of image registration with interlacing and its influence on the dynamic deformations and obtained measurement accuracies.

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Badania zniekształceń dynamicznych obrazów pochodzących z cyfrowych sekwencji filmowych

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Streszczenie

Zobrazowania sekwencyjne, a w szczególności sekwencje filmowe, posiadają cechy, dzięki którym mogą mieć duży potencjał pomiarowy. Należą do nich między innymi systematyka i stosunkowo duża częstotliwość obrazowania, skutkujące dużą liczbą obserwacji oraz podobieństwem sąsiednich obrazów (co ma znaczenie przy automatyzacji pomiarów), a ponadto zmniejszony wkład pracy operatora kamery, możliwość pozyskiwania i przetwarzania w czasie rzeczywistym oraz ogromna i nadal zwiększająca się dostępność zobrazowań. Jednak już na etapie oceny wzrokowej cyfrowych zobrazowań filmowych, zwłaszcza pochodzących z kamer określanych powszechnie jako amatorskie, zauważyć można występowanie pewnych zniekształceń, które mogą mieć znaczący wpływ na wyniki pomiarów. Jest to spowodowane zarówno sposobem rejestracji, z wykorzystaniem migawki elektronicznej i przeplotowego lub progresywnego skanowania, jak i metodami zapisu i kompresji plików. Warto zauważyć, iż są to w dużym stopniu deformacje systematyczne, uzależnione od wzajemnego ruchu kamery i badanego obiektu.

Celem opisanych w artykule badań była próba opisu, typowych dla cyfrowych zobrazowań filmowych, zniekształceń dynamicznych, w funkcji parametrów ruchu kamery względem obiektu, jak również próba zbadania rozkładu deformacji poprzez wykonane w odpowiedni sposób wielokrotne kalibracje kamery, w celu porównania otrzymanych wartości z rozważaniami teoretycznymi. Pierwsza część została wykonana, poprzez wyprowadzenie w oparciu o relacje geometryczne, wzorów, opisujących deformacje dynamiczne obrazu, w funkcji współrzędnych tłowych, prędkości liniowej lub kątowej, czasu rejestracji pojedynczej linii obrazu oraz odległości obrazowej i odległości kamery od obiektu. Część druga, eksperymentalna, obejmowała z kolei analizy rozkładu zniekształceń dynamicznych dla kilku przykładowych sekwencji, zarejestrowanych w trakcie obrotów kamery wokół poszczególnych osi układu współrzędnych. Analizując wyniki eksperymentów, potwierdzono pewną zgodność występujących rzeczywistych zniekształceń z przewidywaniami, które pojawiły się na etapie rozważań teoretycznych. Niestety nie udało się przeprowadzić konkretnych analiz liczbowych, ponieważ na tym etapie nie opracowano jeszcze metody wyznaczenia czasu rejestracji pojedynczej linii obrazu, co uniemożliwiło oszacowanie wartości teoretycznych deformacji.