APPLYING THE LINE FOLLOWING ALGORITHM IN THE CALCULATION OF THE TENSION STRENGTH OF STAY-ROPES OF TOWERS

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ABSTRACT:

A computer system for the determination of the tension strength of a stay-rope has been elaborated. The tension strength in stay-ropes of towers needs to be calculated to approve its verticality and to verify the safety of its exploitation. Traditionally, this was done by means of time consuming methods such as an analog close-range photogrammetry or by means of the theodolite. I present a new approach to this task. The presented technology uses digital images and the computer in order to speed up the elaboration time. It uses the Kodak DCS 760 camera and a laptop as tools. As pictures are taken by a free-orientated, non-metric camera, an appropriate approach to camera orientation should be adopted. I suggest doing this by means of a projective planar transformation, which requires at least four control points. The shape of a freely dangling rope is determined by its tension strength. The catenary equation is used for modeling the shape of the rope. The line following algorithms have been developed for semiautomatic line measurement with sub-pixel accuracy (three points should be placed on the screen by the operator before algorithms can start). As a result, the positions of thousands of points are determined. It gives a more reliable shape of the rope and allows more reliable statistical estimation and evaluation of the results. Catenary parameters are calculated by means of the Least Square Method. As an example, the system was tested on a test field and the results were compared to traditional methods. The obtained results seem to be promising. A fully operable system is now ready to be used. Similar systems, based on line following algorithms but designed for different tasks, such as the determination of fabric chimney rectilinearity, may also be elaborated.

1. INTRODUCTION

At present, there is a widespread use of digital images in close-range photogrammetry.
There exist a number of advantages of a digital sensor, some of which are a high dynamic range (the ratio of the maximal signal coming from a sensor to the noise) and radiometric resolution[1]. A digital image is an ordered collection (a two-dimension matrix) of small, square-shaped elements. One of the important features of digital images, crucial for the realisation of this project, is the possibility to carry out automatic analyses. Automatic analyses are carried out for the purpose of extracting useful information from the image. Extracting geometrical information from an imaged object is extremely common in modern digital photogrammetry. Many automation measurement processes used for DEM determination [2], aero triangulation, and interior orientation are based on digital images. In the project I have developed, automatic measurement has also been introduced. Semi-automatic line following algorithms for measuring the image of stay-ropes of towers have been developed. An integrated computer system for the semi-automatic calculation of the tension strength of stay ropes of towers has been elaborated.
The main disadvantage of using digital images is that the geometric resolution of the sensor is still not sufficiently developed. To improve the precision of automatic measurement and the quality of the final product, sub pixel measurement is usually applied. Sub pixel precision for the line following algorithms elaborated for this project has been introduced.

2. CONCEPTUAL ASPECTS

2.1 Theory

A drilling tower needs stay ropes to maintain its stability and verticality. The ropes are set in at least three directions with a 120° angle between them. Every stay rope has to be pulled out with proper tension strength. The conditions are as follows: tension strengths have to be equal to each other and their value should be kept at a proper level.

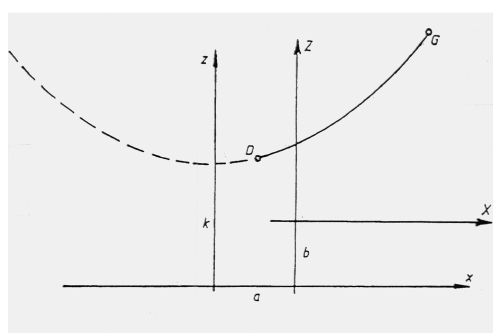

Figure 1: Definition of a catenary parameters, X, Z – a rope plane coordinate system, x, z – a catenary coordinate system.

Strength should be checked every some period of time to ensure the safety of the exploitation of the tower. There are three methods which are used most often. The dynamometric method based on the geodetic survey method, and the photogrammetric method [6]; however, only the last two are useful in practice. The photogrammetric method's significant advantage over the geodetic survey method is its short recording-time (time of taking a picture), which is important during changeable weather conditions e.g. blasts of wind. In this project, the photogrammetric method was used for checking the tension strength.

The classical photogrammetric method consists of basic stages:

- taking a picture of the rope, usually with an orientated phototheodolite,
- measuring the rope in the photograph (usually 6 points), transforming points' coordinates to the rope's system coordinates (with a known camera orientation),
- rendering the shape of the rope approximate to the catenary's model (equation 1 and figure 1),
- calculating the horizontal tension strength component (equation 2) and, at times, also other parameters.

$$Z - b = \frac{k}{2} \cdot (e^{\frac{X-a}{k}} + e^{-\frac{(X-a)}{k}}) = k \cdot \cosh(\frac{X-a}{k}) \tag{1}$$

where: Z, X – coordinates of the rope plane,
a, b, k – catenary parameters,
e – base of natural logarithm.

$$F_x = q \cdot k \tag{2}$$

where: Fx – horizontal tension strength component,
k – catenary parameter,
q –unit weight of the rope [N/m].

2.2 New approach

Although the new method is based on the classical photogrammetric, its realisation has been thoroughly modified in this project.

Main features of the new method are as follows:

- using digital images (no-metric Kodak DCS camera 760 – 2000/3000 pixels),
- employing the photogrammetric method,
- using new technological processing for measurement and computation, which will allow a maximal automation of all stages,
- a large number of points (even thousands) measured in order to determine the shape of the rope,
- using the plain projective transformation for sensor orientation.

There are two main stages of this processing:

- terrain geodetic survey,
- both the automating and computing process.

The first stage deals with the setting out of control points, which should be set into a vertical plane of the rope. The points should form a polygon so that the rope is placed inside of it. The polygon should be as regular as possible. If possible, the control points should form a regular square-shaped pattern throughout all of the rope-area. This guarantees a minimal number of transformation errors.

Practical experiments show that a typical theodolite (e.g. Theo 010) is enough to set the control points into a vertical plane of the rope. No special precision instruments are needed. Although a large number of control points seems to be an advantage, this task is difficult in its practical realisation. The stay-rope is usually a very high object – several dozen meters – therefore, setting out points around it is almost an acrobatic task. A compromise between precision requirements and reality should be made, although six points in one picture is a practical minimum (a minimum of four is required for planar projective transformation but this does not allow error evaluation).

The second stage, which constitutes the main part of my PhD research, consists of three stages:

- measuring the rope and control points on a digital image,
- transforming points' coordinates from the image to the rope plane,
- calculating the horizontal tension strength component.

At first glance it may seem similar to the stages employed in the traditional photogrammetric method but the realisation is entirely different. All stages of the processing are illustrated in figure 2.

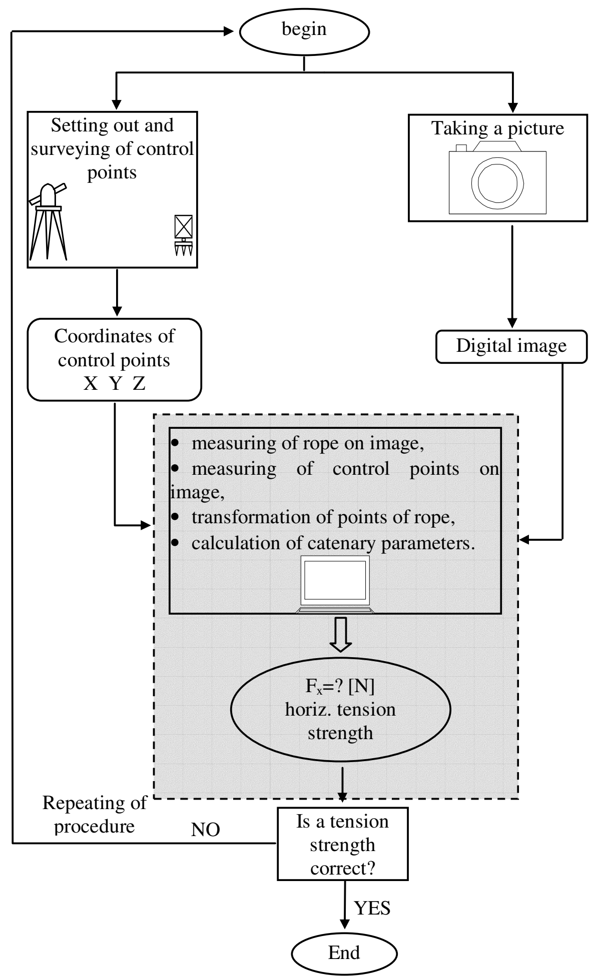

Figure 2: Processing stages of the correction of the stay-rope tension strength.

The terrain geodetic survey involves the setting out and surveying of the control points. The points should be set in a way that they can fit into the rope plane. For the sake of simplicity, usually two of them are chosen as the upper and the lower catch of the rope. Others are artificial control points marked with signals placed on a tripod and on the construction of the tower. It is of great importance to remember that the points should be placed around the rope so that the whole measured part of the rope is placed inside the polygon formed

by the control points. This requirement is important for obtaining a high precision of transformation.
The picture has to be taken so that the whole rope (the lower catch and the upper catch) is visible in it. Otherwise the catches could not be used as control points.
Experience shows that, in order to get reliable results, at least 60 % of the rope's length should be available for measurement.

The automating and computing process begins with taking picture(s) (at least one) of the rope with a digital camera. Pictures are then transmitted on site from the camera to the computer. When in the computer, the pictures can be screened by an elaborated system and all processing activities, such as control points measurement, rough rope's position determination, running the line following algorithm, and, finally, computation of the horizontal tension strength component of the rope, are carried out. A human operator determines control points and rough rope's positions manually - further steps are automated. When control points are measured and the position of the rope is marked, the line following algorithm is activated. When the work of the line following algorithm has been completed, the results are displayed on screen as green points marked on the rope. When the human operator evaluates the results, he/she can decide whether to repeat the line following analysis or to proceed to the next step, i.e. the computation of the horizontal tension strength component of the rope.
When the final horizontal tension strength component of the rope is determined, the decision concerning applying proper correction to the rope's tension and repeating the entire process is made.

The computation of the horizontal tension strength component of the rope consists of two steps. The first one is the computation of catenary parameters (equation 1, figure 1) in the iteration process of the Least Square Method. Usually, a large number of points is gained after finishing the work of the line following algorithm– in the example tested, there were about 1600 points. The iteration process did not last too long – usually after three iterations sufficient accuracy was obtained. With the catenary parameter *k*, the calculation of the horizontal tension strength component of the rope becomes very simple and functions according to equation 2.

3. LINE FOLLOWING ALGHORITHM

Before line following algorithms were elaborated, a thorough analysis of rope images had to be carried out.
The rope image can be considered as being shaped as a longish hump or ditch, depending on whether the image is negative or positive. An example of a rope's image, approximated by a kriging interpolation is shown in figure 3.
The image of the line can be modelled by a mathematic function. Such an introduced model was based on [3]. Here I only notice two conditions that should be fulfilled by a curve received by the slicing image of the rope (along a row or column) with a vertical plane:

- Possesses a continuous first and second derivative,
- Possesses one maximum and two inflection points.

A model of such a function is shown in figure 4a.
The task of the line following algorithm is the semi-automatic determination of a set of points along a ridge of a hump (maximum of the function). The result scores in numerous (thousands) semi-automatically measured points.
The procedure runs/occurs in following steps:

- A human operator places three points to show an approximate shape of the rope curve,
- The line following algorithm is activated and automatic measurement is carried out.

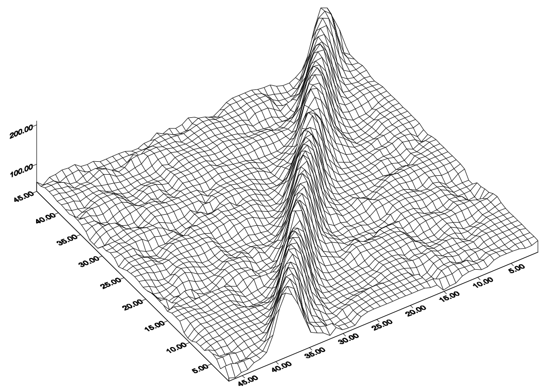

Figure 3: An axonometric view of a digital image of a rope. The pixels are units of horizontal coordinates and their grey level are the units of vertical coordinates. The original function of the image was interpolated by the kriging.

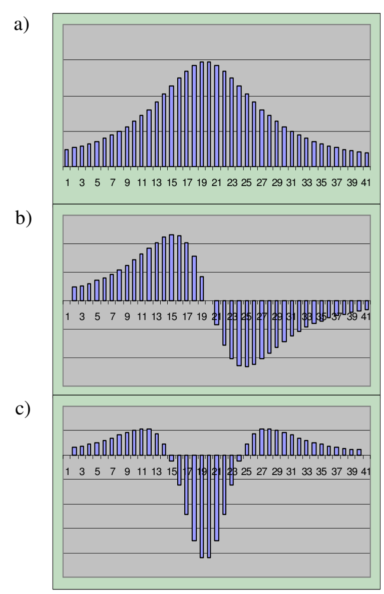

Figure 4: a) Function of the rope image, b) first derivative, c) second derivative.

Points which define the rope should be placed along the whole length of the rope, the first one close to the upper catch, the second in the middle, the third close to the lower catch. The line following algorithm starts from the first point and stops on the third. The analysed segment of the rope should be as long as possible in order to minimise the number of errors in the results and assure their reliability (paragraph 2.2).
While the line following algorithm is working, the first step is to fit the catenary into the three above-mentioned points. This procedure runs in two courses. In the first course, inflection points are identified with pixel resolution.

After the first course is finished, the average positions of left and right edges of the rope are determined. These are to be used in the filtering process at the end of the procedure. In the second course, sub-pixel positions of the centres of rope (as the average of positions of inflection points) are calculated at every interval and the filtering of erroneous points is carried out.
In a more detailed description, in the first course, the procedure starts from the starting point and forwards every single pixel until the end point. The position on the rope (according to the catenary equation) is calculated for every pixel. In this position, raster image analysis is carried out in a strip of a pixel. The length of the analysed strip constitutes the parameter of an algorithm and can be changed from 21 to 49 pixels (only an odd number of pixels in strips is allowed).

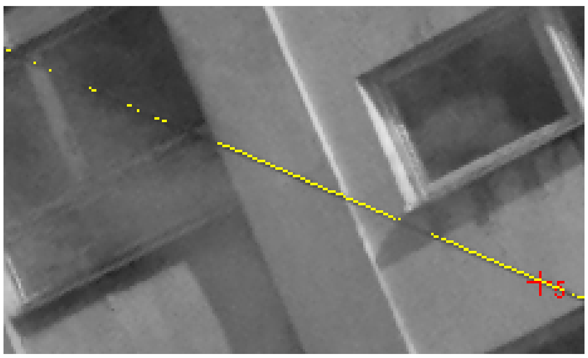

Figure 5: The result of the line following algorithm execution. Rope points identified by the algorithm are marked white. In some areas points could not be identified properly and they were filtered out.

The analysed strip of a pixel is placed vertically (along a column – figure 6) or horizontally (along a row). The placement of the strip depends on the angle between the lines made by the first and the third point of the approximate rope placement and the row direction (inclination angle). When the angle is bigger than 45 degrees, the strip is placed horizontally, when it is smaller than or equal to 45 degrees, the strip is placed vertically. The middle of the strip is put exactly in the position calculated by the catenary equation (for three approximate points). Strip placements are calculated for every pixel along abscissa (row or column depending on inclination angle). The described situation is shown in figure 6. During the analysis, inflection points of the function of the rope's image are found by means of the first derivative (see figure 4 b – extremes of function). In an actual implementation of an algorithm, two sets of points are stored, one for the left edge of the rope and the second for the right edge of the rope. The average positions (left and right edges) are calculated according to the beginning of the analysed strip (equation 3).

$$D_{av} = \frac{\sum_{i=1}^{n} di}{n} \qquad (3)$$

where: D_{av} – average position,
n – number of pixels,
d_i – i^{th} distance between beginning of strip and inflection position, in pixels.

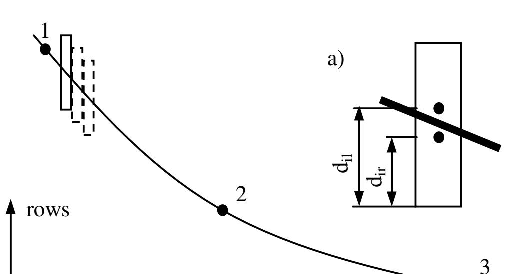

Figure 6: The scheme of the rope image analysis for an angle between the 2-3 line and row direction of less than 45º (analysis along the column). a) – A single analysed strip magnification, the position of the left and right inflection points marked by black points.

In the second course, after all approximate inflection points positions for the left and right edge of the rope have been recorded and the averages have been calculated, exact sub pixel positions of the rope (highest points of the hump in figure 2 or 4a) are determined with a second derivative.

Practical experience shows that in some areas miscalculations may occur. Such points are eliminated by the filtering execution. Eliminated points are not taken into consideration for further processing. Such filtering consists of the eliminating of blunders by checking whether the value of the deviation exceeds the threshold. The value of the threshold is the parameter of the procedure and its value is set empirically.

The filtering process takes place during the second course of the algorithm. At every analysed strip placement (the same as in the first course), sub pixel positions of the right and left inflection points are determined by a linear interpolation of the second derivative – figure 4c). Absolute differences between such positions and the averages calculated in the first course are compared to its threshold value. When at least one of them exceeds it, both are eliminated. The exact sub pixel position of the rope (ridge of the hump) for elementary strip placement is the average of sub pixel positions of both inflection points. The resulting set of rope points' coordinates is stored for further processing.

A more detailed description of the algorithm can be found in my PhD thesis, which is available in the AGH library – (University of Science and Technology in Krakow.)

Miscalculated points (which have to be filtered out) occur in areas with a weak contrast between the rope and its background. Very good results are achieved from the areas with a homogeneous background and sufficient differences in grey values of the pixels between the rope and the background. The final result of the line following algorithm is shown in figure 5 (homogeneous and non-homogeneous areas can be identified). As a significant magnification of image noise constitutes one of the features of derivatives, a noise eliminating filter (low pass) is advised to be run/employed beforehand [5].
Another detail worth mentioning here is that in the line following algorithm, an assumption has been made that the line in the image can be modelled with catenoid equation (equation 1). In other words, the catenoid after the projective transformation still remains a catenoid. Although this has never been proved in theory, practical results show that this may be the case.

4. PRACTICAL RESULTS

Experiments for a practical verification of the elaborated system have been carried out. Pictures were taken from the terrain test field. The stay-out ropes of the laundry chimney of the Military Hospital in Wrocławska Street in Kraków were chosen as a test field (figure 7). The test field was quite small: the vertical length component of the rope was 21.2 m long and the horizontal length component of the rope was 17.6 m long.
Eight control points were set out into rope's plane, as marked in figure 7. The rope was measured by three methods:

- The geodetic survey method (with theodolite),
- The classical photogrammetric method (photogrammetric camera Photheo 19/1318 was used),
- The new photogrammetric method (with the digital non-metric Kodak DCS 760 camera).

All acquisitions were made from the same distance of about 45 m. In the geodetic survey and the classical photogrammetry instance, instruments (theodolite, camera) were set on a tripod at known coordinates and at a known camera orientation element. In the case of the new photogrametric method, the picture was taken manually with unknown camera orientation elements.

Figure 7: Picture taken on a test field with the Kodak DCS 760 digital camera.

The scale factor for the Photheo 19/1318 camera was m_c = 230 and the scale factor for the Kodak DCS 760 camera was m_c = 900. This means that the precision of the Photheo camera is 900 : 230 ≈ 4 times better.
There were two versions of the classical photogrammetric method. In the first version, a traditional measurement of glass plates on a stereo-comparator was carried out. In the second version, scanning of glass plates had been done before the measurement of images on the digital station.

In table 1, accuracy characteristics of pictures are put together. According to table 1, we can see that the classical analogue method is still more accurate than the new digital method (except for the last row, commented below).

Camera name	Angle precision ’’	Image pixel size µm	Terrain pixel size mm	Scale factor	c_k mm
Photheo 19/1318 (traditional)	3.2	3.0 (assumed for analogue pictures)	0.7	230	194,92
Photheo 19/1318 (scanned)	22.2	21.0	4.8	230	194,92
Kodak DCS 760	37.2	9.0	8.1	900	50.00
Kodak DCS 760 (sub pixel)	0.5	0.12	1.1	900	50.00

Table 1. Accuracy characteristics of pictures.

In table 2, the results of all the applied methods are put together. The information provided is: *k, a, b* – catenary parameters, m_k – the mean squared error of *k*. F_x, m_{Fx} – the horizontal tension strength of the rope component and its error, calculated by the law of error propagation based on equation 2 (weight unit of the rope *q* is considered as errorless).
During the experiments, other line following algorithms were tested; however, the one which gave the lowest m_k is the only one presented here (paragraph 4), as it determines the catenary most accurately.
It can be seen that the lowest m_k was received by the new method. The value of the tension strength is the same for all methods with the exception of the classical photogrammetric method (traditional). However, 1 N difference is of no practical consequence. Although we do not know the real tension strength, the values from independent methods have proved their reliability. The most important thing is that the value received by the new method is in the range of the values received by other methods.

Method applied	k [m]	a [m]	b [m]	m_k [cm]	F_x [N]	m_{Fx} [N]
geodetic survey based method	51.80	49.46	−67.55	3.8	457.0	0.3
classical photogrammetric (traditional)	51.94	49.63	−67.81	6.9	458.0	0.6
classical photogrammetric (scanned)	51.82	49.49	−67.59	4.2	457.0	0.4
new method Kodak DCS 760 camera	51.80	49.48	−67.58	0.7	457.0	0.06

Table 2. Comparison of obtained results.

It has been said above that the line following algorithm results in sub pixel resolution (paragraph 4). A very simple analysis was carried out to determine the sub pixel resolution of the line following algorithm. The mean square error of the rope position determined by the residuals was 1.1 mm, with the assumed scale factor of m_c = 900. In the image we have 1.1 µm, which results in 1.1/9 ≈ **0.12** pixel (9 µm is a pixel size).
Table 1 can be slightly modified. The new method precision for sub pixel resolution is put in the last row of the table. The result from the last row should not be paid too much attention to, as it is merely an illustration. Pictures in different scales will probably result in slightly different sub-pixel resolution. More experiments on different test fields and with different scales should be done in order to draw more reliable conclusions.

5. CONCLUSIONS

A system for the semi-automatic determination of the tension strength of a stay-rope has been elaborated and practical experiments have been carried out. The system is based on the photogrammetric method, which has been adopted in new conditions. New technological processing has also been developed. This requires special conditions to be satisfied for setting out the control points (paragraph 2.2). This also requires high tech electronic equipment such as a laptop, digital camera (Kodak DCS 760 for the described project), and a picture transfer between camera and computer (cable connection). An elaborated computer program is the heart of the system. It enables such operations as image visualization, control points measurement, showing the placement of the ropes in the image, line following and carrying out the computing of the tension strength. The program works under the supervision of a human operator. The operator performs the above mentioned measurements and decides about proceeding to the next step of processing (after the previous stage has been finished).

Some further conclusions and information about the system are listed in points below.

- The rope image has to be wide enough to be able to run the line following algorithm (at least 7 pixels), i.e. scale factor (m_c) should be appropriate,
- An automatic measurement of the rope is most reliable in areas with a homogenic background and a good contrast between the rope and the background (e.g. the sky in the background); such ideal situation does not constitute a rule, which is why further steps should be made,
- The filtering algorithm has been elaborated in order to deal with miscalculated points; practical results of the work of this algorithm have been promising.
- The results received by the new digital method are similar to those received by the traditional method but the error is smaller. This can be explained by a large number of well-fitting points (≈1600) used for the estimation of parameters,
- The new technology shortens the time of the process– after control points have been set out and their coordinates have been determined, the whole process, from the taking of the picture to the receiving of the result, takes only a few minutes,
- The system works almost in real time, which is why correction can be done onsite and the whole process can be repeated as many times as required,
- The sub-pixel resolution of the line following algorithm was evaluated at ≈0.12,
- The photogrammetric method's advantage – short registration time of the whole rope - may be used for a more complex treatment of the tower and its ropes; all objects registered in one picture allow us to calculate tensions in all ropes and, possibly, even check the tower verticality for one moment in time. This can be possible in the future; at present, however, sensor resolution is still limited.

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