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A Vision-Based Technique for Lay Length Measurement of Metallic Wire Ropes

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Abstract—

The lay length of metallic wire ropes is an important dimensional quantity whose analysis is useful to highlight rope deformations due to distributed damages. This paper describes a measurement system which is based on a video camera and an off-line processing algorithm. The camera acquires an image sequence of the running rope, then an image processing algorithm extracts the rope contour and measures the distance among rope strands and the whole distance covered by the rope during the test. A mathematical model of the rope contour has been developed and employed to test the proposed algorithm with simulated data. In field tests have been carried out on a working aerial cableway using a general purpose camera.

Index Terms— Steel wire rope, non-destructive test, vision system, sine-fit, phase unwrapping.

I. INTRODUCTION

Steel wire ropes are widely employed both for people transport (ropeways, chairlifts, elevators, ...) and for goods movement (cranes, platform lifts, ...). Periodical inspections are necessary in order to verify the rope integrity and to early detect small damages. Non destructive tests (NDT) such as the visual and electromagnetic inspections are mandatory and must be carried out at predefined intervals according to local regulations [1],[2]. Other NDTs are required in particular demanding applications or in the presence of suspicious cases [3]. Among all the available NDTs, the measurement of the rope length, full or local, is a simple procedure that provides useful information about the rope status. The rope length is set during the design of the transport system, but it can change during the rope life because of several reasons such as settling-in and aging phenomena, as well as abrasion and corrosion that cause a local reduction of the rope section and, consequently, a local lengthening. A non-uniform lengthening could be a symptom of a progressive, internal corrosion, which is not often detectable by means of a simple visual inspection method. Unfortunately, the rope length is difficult and costly to be measured in working conditions without removing the rope itself from the appliance. The local length is easier to be measured provided that a “well defined” piece of rope, such as the rope lay, is defined. Metallic wire ropes are composed of high carbon steel wires twisted in order to form strands. A group of strands is helically

wrapped around the rope core, which is often made of a non-metallic material. This particular structure makes the rope highly flexibility while maintaining high breaking limits. The number of strands and their directions depend on the rope application. As an example, Fig. 1 depicts a standard wire rope consisting of six external strands that are laid in the right-hand side direction.

Wire and strand directions are important characteristics of the rope that are often referred as the “rope lay”. Any change of the rope length produces a change of the lay length, which can be defined as the length of a strand turn. In Fig. 1 the lay length is six times the distance between two contiguous strands, provided that the rope is uniform.

Procedures for the lay length measurement have been defined by the rope manufacturers and by the operators devoted to the rope inspection. As an example, the length can be measured marking one strand on the rope and then performing an average length measurement over some turns of the same strand [3]. A rough estimation of the measurement uncertainty can be carried out by considering that the main uncertainty contribution is due to the identification of the beginning and the end positions of the strand turn. For practical reasons, this uncertainty can be hardly maintained lower than a couple of millimeters, thus obtaining a relative length uncertainty of about a few units in 10^3 .

This measurement procedure is effective but it cannot be employed to monitor the lay length over the full rope extension. Moreover, it cannot be employed to carry out measurements on a moving rope. For these reasons, the authors have developed a system for the automatic lay length measurement of the full rope, which constitutes of a vision system and of an image and signal processing algorithm. The vision system acquires several, consecutive rope pictures that are employed to extract the rope profile. Analyzing the profile it is possible to measure the distance among consecutive strands and, therefore, the lay length.

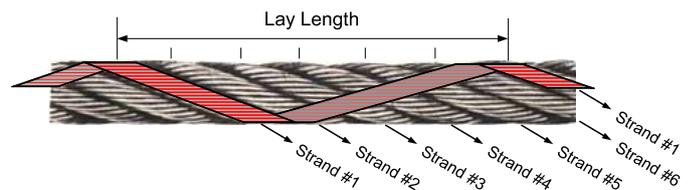


Fig. 1. The lay length of a rope composed of six strands.

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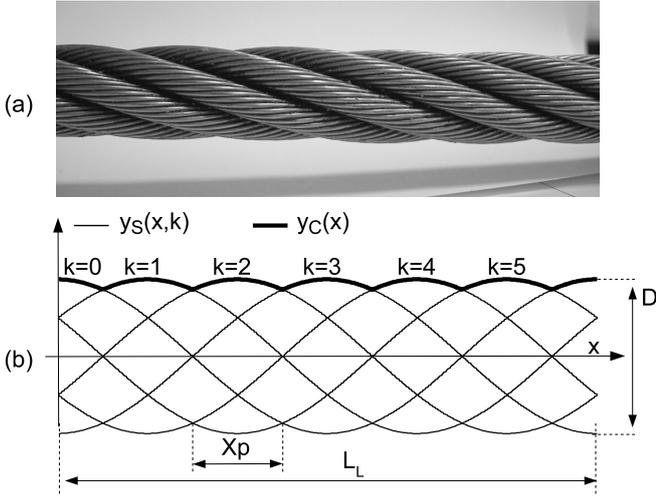


Fig. 2. The proposed mathematical model of the rope contour. This model is employed to test the algorithm effectiveness.

II. THE ALGORITHM FOR THE MEASUREMENT OF THE ROPE LAY LENGTH

The contour of a rope in a given image is a periodic function whose period is the distance between two consecutive strands. A modified sine-fit algorithm is employed to estimate the fundamental component of the rope contour in order to measure its period. Eventually, the lay length is simply obtained multiplying the contour period by the number of strands.

Fig. 2 (a) shows a high resolution image of a stranded rope. The contour of the rope image can be approximated as the envelope of a group of delayed sinusoids where each sine wave $y_S(x, k)$ represents the k^{th} strand and, with reference to Fig. 2, it can be expressed as:

$$y_S(x, k) = \frac{D}{2} \cdot \sin\left(\frac{2\pi}{N_S \cdot X_P} \cdot x + \frac{\pi}{2} - k \cdot \frac{2\pi}{N_S}\right) \quad (1)$$

where N_S is the number of strands, D is the rope diameter and X_P is the linear period of the rope contour along the rope axis.

The strands are equally spaced so the rope contour $y_C(x)$ is:

$$y_C(x) = y_S(x, k) \quad (2)$$

where $k = \left\lfloor \frac{x}{X_P} + \frac{1}{2} \right\rfloor$

Once the rope contour has been extracted from images, its period X_P can be obtained by fitting a sinusoidal function as shown by Fig. 3. According to the figure, the fitting function can be written as:

$$y_F(x) = A_P \cdot \sin\left(\frac{2\pi}{X_P} x + \varphi\right) + A_0 + A_L \cdot x \quad (3)$$

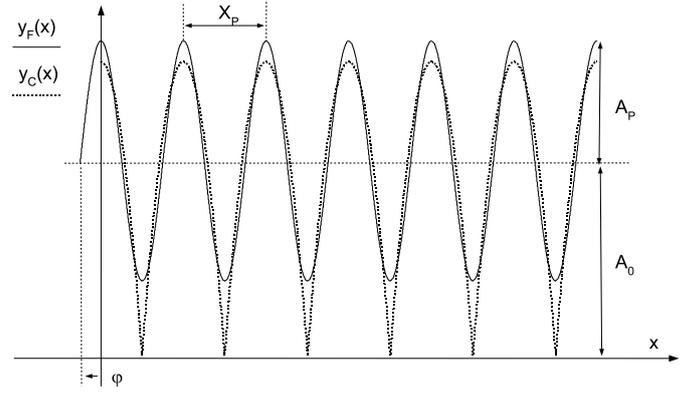


Fig. 3. The rope contour $y_C(x)$ and the fitting function $y_F(x)$.

where A_P is the sine peak amplitude, A_0 is an offset term, φ is a phase delay due to the position of the rope at each frame and A_L is a linear term that takes into account the non-perfect alignment of the picture with respect to the rope axis (not shown in Fig. 3).

Equation (3) can be rewritten as:

$$y_F(x) = A_C \cdot \cos\left(\frac{2\pi}{X_P} x\right) + A_S \cdot \sin\left(\frac{2\pi}{X_P} x\right) + A_0 + A_L \cdot x \quad (4)$$

in this way, the parameters $[A_C, A_S, A_0, A_L]$ are obtained using a linear least square fitting method, whereas the period X_P is obtained in a recursive way [4].

In order to test the effectiveness of the proposed fitting method, a set of rope contours has been numerically generated using Eqn. 2 and the contour period was estimated by fitting the function of Eqn. 3. Simulation results here described refer to test conditions similar to the experimental ones that will be described in the next section. The simulated contour has a length of 100 mm and it has been quantized as if it was extracted from rope pictures having a resolution of 640x480 pixels. The simulations have been carried out for different profile periods X_P and for different profile amplitudes. The number of contour periods in each simulated frame swings from about 7 periods, when $X_P = 15$ mm, to only 2 periods for $X_P = 50$ mm.

Fig. 4 shows the expected standard deviation as a function of the rope period X_P for contour amplitudes ranging from 2 pixels to 10 pixel (peak-to-peak values). The standard deviation has been obtained, for each period value and for each amplitude, by processing 200 contours with random phase. In order to avoid correlation errors, the amplitude was not set as a constant, but a random value up to one pixel was added at each test. Overall, about 10^7 simulations were carried out.

Fig. 4 shows that the error grows reducing the contour amplitude because of the quantization error effects. The error also grows increasing the rope period. This is due to the reduced number of contour periods available in each image in the presence of large periods. This aspect can be taken into account to set the camera view angle. A

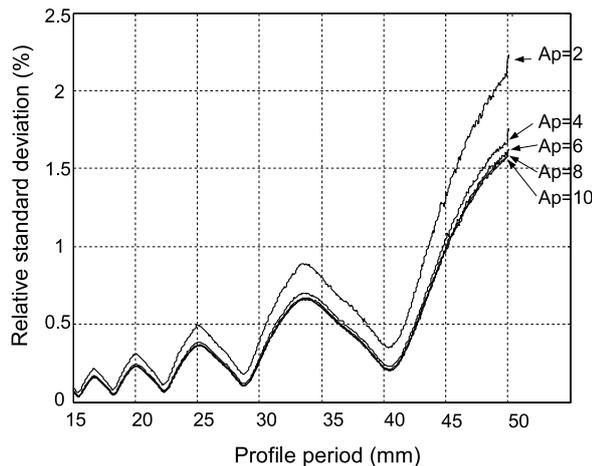


Fig. 4. The relative standard deviation of the contour period obtained by simulation.

wide angle provides images that contain several contour periods but with a reduced amplitude that is contained in few pixels only. On the contrary, a small shot angle produces opposite effects. According to the simulation results, a contour amplitude greater than 6 pixels provides negligible advantages. The main error source is related to the strong distortion of the contour period [5], that is mainly due to the presence of a second harmonic. For this reason better results could be obtained using a more appropriate fitting function that takes the rope contour shape into account.

III. MEASUREMENT OF THE ROPE POSITION

The algorithm described in the previous section provides a measure of the lay length at each acquired frame. If the vision system is based on a general purpose “frame-based” camera, like the one employed to perform the experimental tests, the frames are continuously acquired at a fixed frame rate. In this conditions the lay measurements cannot be associated to the rope position, since this quantity is not measured during the test.

Anyway, in most practical cases it is important to know at which rope position a sudden change of the lay length occurs, so that the suspicious part of the rope can be easily identified and further examined. Moreover, a progressive degradation of the rope can be highlighted by comparing the results of the tests carried out during the full rope life.

The measurement of the distance covered by the rope during the test can be obtained in several ways, e.g. using running wheels or encoders [6]. Some of these methods can be effectiveness, but they require independent and dedicated instruments that increase the complexity of the measurement system.

On the other hand, a continuous measurement of the rope position can be carried out using the same vision system already employed to acquire the rope frames. Some cameras, in fact, can be synchronized either with the motor driver of the transport plant or with an encoder, so that the

frames are acquired at uniform distance intervals instead of at uniform time. Using this approach, further benefits can be obtained replacing the “frame-based” camera with a “line-scan” camera able to acquire only a thin slice of the rope image but with a remarkable high resolution. A rope image of arbitrary width can be thus reconstructed merging several camera acquisitions. Using this approach, the resolution of the rope images is higher than in the case of frame-based cameras, virtually overcoming the trade-off between the image resolution and the length of the rope image. Moreover, when the camera is synchronized with the transport plant, the position of each rope image can be easily identified.

The solution proposed in this paper employs the vision system to measure both the lay length and the position of the rope at each acquisition. Anyway, it does not require neither independent measurement instruments nor synchronization systems thus minimizing the complexity of the measurement system.

Measurement of the frame position by means of a LPA algorithm

In the fitting function that we used to model the rope profile, we inserted a term φ that considers the phase of the rope profile acquired at each frame. The phase is related to the position of the rope with respect to the camera and it can be therefore employed to measure the distance covered by the rope during the test. The knowledge of the distance is useful to localize the acquired frames and it can be employed to compare results obtained during different tests.

When the rope covers a distance equals to the distance existing between two consecutive strands (X_P , the contour period in Fig. 2) the corresponding phase shift is equals to 2π . By measuring the phase it is then possible to measure the distance since the period of the rope contour is known as it has been obtained with the fitting procedure previously described.

The phase the fitting algorithm returns is a number in the range $[-\pi, \pi)$, therefore it can be considered as a *wrapped phase* that, in our application, has to be unwrapped in order to derive the *absolute phase* of the rope contour and therefore the distance. The absolute phase would enable the correct sequencing of the fitted sinusoids throughout all the acquisition frames, thus allowing a continuous rope displacement estimation.

The unwrapping algorithm is trivial in the presence of phase samples not corrupted by noise, but in our application the phase noise is significantly high because of the sine-fit performance in the presence of non-sinusoidal rope profiles. Moreover, in order to use low cost cameras, we have to face with a reduced frame rate so the phase signal is also strongly aliased. As an example, if the frame rate is of 50 frames per second, the rope speed is of 2.5 m/s and the distance between two consecutive strands is of 25 mm, the absolute phase increase is 6π rad at each frame acquisition, while the wrapped phase remains constant.

The absolute phase, in the following indicated as ϕ , and

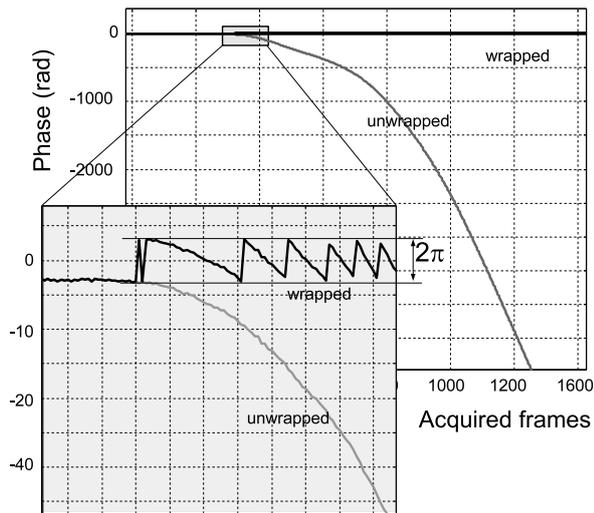


Fig. 5. Example of the phase unwrapping algorithm. The LPA techniques derives the unwrapped phase (gray line) from the wrapped phase (black line). The expanded panel represents the time interval when the rope begins to move.

the wrapped phases φ are related by the following formula:

$$\phi = \varphi + 2k\pi$$

where k is an integer. The wrapping of the phase can thus be seen as an operator that projects the absolute phase ϕ into the wrapped phase φ by counting in modulo 2π [8]. If φ is the output of the fitting algorithm on a given frame of the sequence, the absolute phase ϕ has to be calculated by relying on different considerations. In practice, this means that we have to estimate the integer value of k , which is required to unwrap the phase obtained by processing each frame.

We applied a local polynomial approximation algorithm (LPA) to perform phase unwrapping. The requirement is that the camera recording starts when the rope is in a fixed position and is not moving. In this condition, we can say that the sinusoid in each frame has to start at the same position, hence $\phi = \varphi$. When the rope starts moving, the absolute phase starts increasing (or decreasing, depending on the motion direction), until it reaches a value close to $\pm\pi$, when wrapping begins (see Fig. 5). Our LPA unwrapping procedure employs a second-order polynomial function that interpolates the previously unwrapped samples in a window whose width is of some tenth of phase samples. The interpolation is employed to predict the future unwrapped phase sample that allows for estimating the number k of phase wrapping.

The above mentioned method is theoretically robust with respect to the rope velocity. Because the employed LPA is based on a second order polynomial, the major issue regarding the applicability of this method is not related to velocity, but to acceleration. The rope must move at constant speed or at a constant acceleration. Smooth acceleration changes can be tolerated but in tests where the acceleration changes quickly, the order of the LPA needs

to be changed accordingly. Anyway, in the practical cases concerning the tests carried out on real transport plants, a LPA up to the second order is almost always appropriate.

Noise represents the major threat to a correct phase estimation. In the presence of a sub-sampled phase signal, like in the tests described in the following section, a phase noise greater than π causes an error in the estimation of the number of phase wrapping k . Noise sources, as previously described, are mainly due to quantization of the rope profile as detected by the recording equipment and by the number of periods in a single frame, but another noise source can be due to a poor image quality because of rope imperfections. For this reason, the robustness of the LPA algorithm can not be guaranteed even in presence of a suitable acquisition system and when the test is carried out at constant speed. Anyway, suspicious cases can be highlighted, e.g. considering the residual error of the fitting algorithm.

IV. EXPERIMENTAL RESULTS

The proposed measurement system has been employed to monitor the hauling rope of an aerial cableway (see Fig. 7). The rope has a nominal diameter of 22 mm and has a right-hand lay composed of six strands. The nominal length of the rope is 2329 m.

The video recording system consists of a general-purpose, low-cost camera with a resolution of 720x576 pixels that acquires interlaced frames at 25 Hz of frame-rate, according to the Television European Standard (PAL). The video acquisitions were carried out during some cableway trips in order to monitor the rope lay length along the full rope extent. The shutter time was set to the minimum available value of 1/2000 s. Because of the high shutter speed, a 1 kW halogen lamp was employed to light the rope. The lamp was located in order to have a grazing light also useful to highlight the strands while reducing the lighting of the background.

The camera was located in front of the rope at a distance of about 1 m and the optical zoom was set, depending on the test, at different values in order to acquire rope portions from 100 mm to 200 mm. These values are a good trade-off between the number of strands, from 4 to 8 per image, and the resolution of the rope profile, from about 6 to 3 pixels peak-to-peak.

Fig. 6 shows the intermediate results of the processing algorithm that is composed of an image processing phase followed by a signal analysis procedure. The frames are extracted from the video (Fig. 6, A) and each frame is de-interlaced thus obtaining pictures (Fig. 6, B) having a resolution of 720x288 pixels and acquired at 50 frames per seconds. Each image is then cropped and converted to grayscale (Fig. 6, C). To make the algorithm as independent as possible on the lighting conditions and on the background, the image intensity is rescaled. The average intensity value of the pixels belonging to the background is mapped to white and the remaining pixels are rescaled

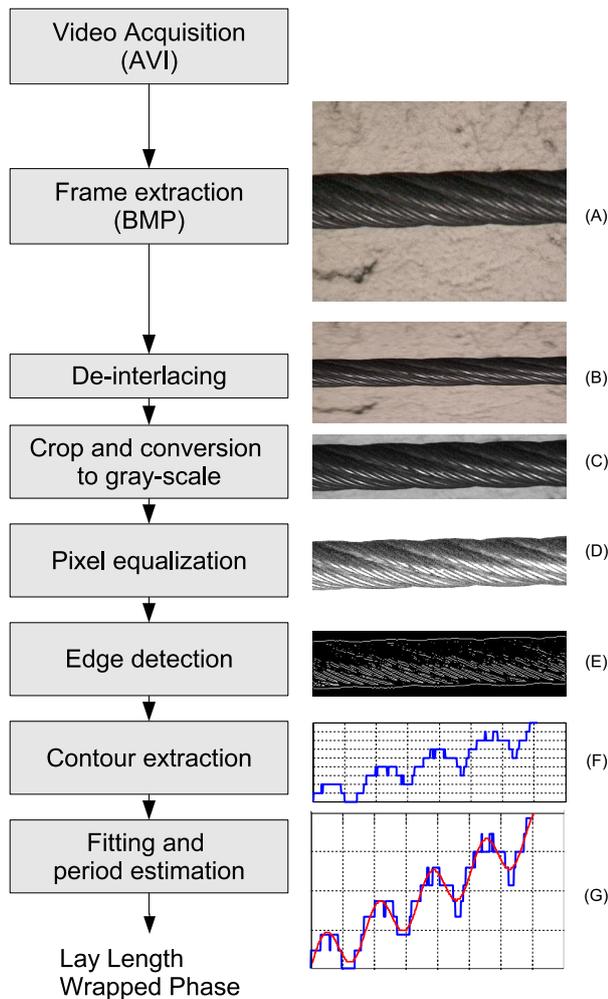


Fig. 6. The processing algorithm: each frame is processed independently after de-interlacing. Image crop, gray-scale conversion, and equalization prepare the image for the contour extraction (by an edge-detection algorithm). The extracted contours is then fitted.



Fig. 7. The set-up arranged for the image acquisition.

accordingly, using a linear transformation of the grayscale colormap (i.e., gamma correction equal to 1). To calculate the average intensity of the background, we manually selected a square region of 50x50 pixels (Fig. 6, D).

The contour of the rope image (Fig. 6, E) is extracted by an algorithm based on the Laplacian of Gaussian method [7]. The lay length can be considered constant for rope portions of some meters, so the acquired rope profile can be considered, at least for each frame, a portion of a periodic function. The extracted rope contours are strongly corrupted by quantization noise, as expected (Fig. 6, F).

In the next step the fitting algorithm is employed to estimate the contour period (Fig. 6, G) and eventually the lay length.

The lay lengths obtained during two tests are shown in Fig. 8. A FIR moving average filter composed of 200 coefficients was also applied in order to average the measurements over a rope length of about 6 m. The distance covered by the rope during the tests has been obtained, as previously described, unwrapping the phase. The distance has been here employed to plot the lay length as a function of the rope distance; in this way it is possible to easily overlap the two curves in order to compare the lay length at the same position.

The tests were carried out at different rope speeds and setting different view angles in order to test the proposed system in different conditions. During the first test, the camera view angle was set in order to take rope pictures about 100 mm wide. The rope speed was of about 1.5 m/s so the video acquisition lasted 32 minutes and about 110000 frames were analyzed. During the second test the rope speed was increased to 2.5 m/s and the view angle was modified in order to acquire rope pictures 200 mm wide. According to the simulations, the expected standard deviation of the lay length should be smaller than 0.3% in both tests.

In the first test, the lay length was measured at the beginning of the rope with a manual method [3] based on the direct measurement of a multiple of the lay length. The start position of a strand was identified and marked over the rope surface and the end position was marked after six turns of the same strand. Because of practical reasons, mainly due to the difficult access to the rope, the uncertainties of both the start and the end positions were of few millimeters. The measurement of the lay length was thus 165.0 mm with a standard uncertainty of $u=0.7$ mm. This value was employed to calibrate the system.

The standard deviation of the measurements obtained when the rope was stationary (section A in Fig. 8), and before the filtering, is of about 0.34 %. Both the standard deviation and the maximum error, shown in a previous work [9], are in agreement with the simulation results (Fig. 4).

According to the obtained results, the first part of the rope (about 60 m) presents a non-uniform wrapping while the lay length is approximatively constant in the remaining part. The standard deviation of the measurements carried out when the rope was running at full speed is of about

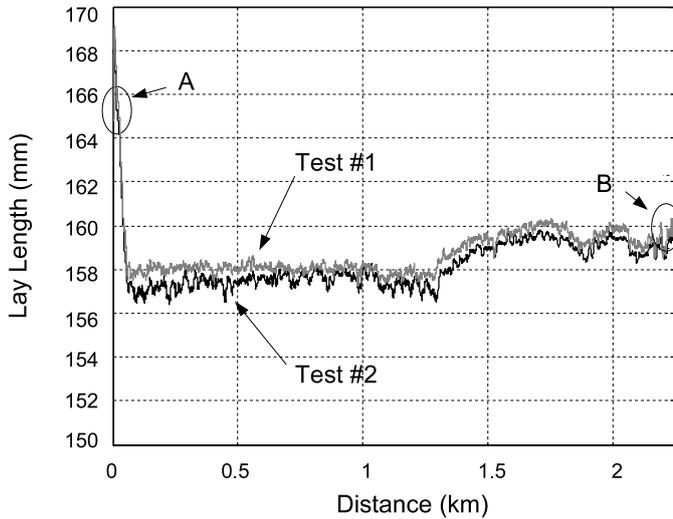


Fig. 8. The lay length measured with two tests carried out at different conditions. Comparison measurements with a different method were carried out at the beginning and at the end of the rope (sections A and B).

Lay Length	Manual Method	Vision system
Section A	165.0 mm u = 0.7 mm	165.0 mm (cal.) u = 0.9 mm
Section B	159.4 mm u = 0.7 mm	160.0 mm u = 1.2 mm

TABLE I

COMPARISON BETWEEN THE RESULTS OBTAINED WITH THE PROPOSED VISION SYSTEM AND A MANUAL METHOD.

1%. This value is greater than the one obtained through the simulations because of several factors such as the rope vibrations, the not negligible shutter time and the image imperfections caused by rope dirtiness and grease.

At the end of the test (section B in Fig. 8) the system returns a lay length of about 160.0 mm with a standard uncertainty of about 1.2 mm. The uncertainty here considered is due to the calibration uncertainty and to dispersion of the results. For comparison purposes, the lay length was measured at the end of the rope with the manual method thus obtaining the value of 159.4 mm, standard uncertainty of 0.7 mm, that is in agreement with the result obtained with the proposed measurement system.

Comparison results are summarized in Table I.

The distance covered by the rope was obtained unwrapping the phase of the fitted sine-wave by means of a second order sliding LPA. The width of the LPA window was set empirically in the range of 10 samples to 100 samples, depending on the test conditions.

Fig. 9 shows the distance covered by the rope during the first test, and the figure also shows the rope speed that has been numerically obtained deriving the distance. The rope length estimated after the complete phase unwrapping is 2372 m.

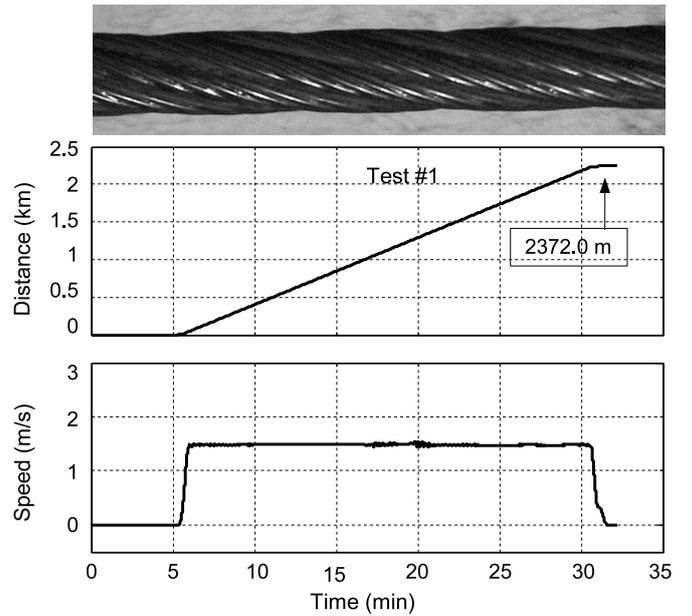


Fig. 9. Distance and rope speed obtained during the first test where the view angle was of about 10 cm and the rope speed was of about 1.5 m/s. A frame of the rope is shown at the top of the figure.

The distance was again estimated during the second test (see Fig. 10) concerning the same rope, thus obtaining 2372.7 m. During these tests was not possible to compare the results concerning the rope length with traceable instruments able to operate in working transport plants. Anyway, the difference among the measurements obtained with the proposed vision system is of few units in 10^3 , value that has been confirmed by other tests carried out in similar conditions. This is an interesting result not easily achievable with other methods, such as the ones based on running wheels typically employed to measure the rope length [6].

In this application, the main responsible for the distance uncertainty is the LPA algorithm, which is not able to correctly unwrap the phase in the presence of noisy rope frames. This method shares with other distance measurement methods several uncertainty sources, such as the rope temperature, the rope mechanical stress, the identification of the rope starting position and the calibration uncertainty. These sources have been investigated in another work [6] and are here not relevant since the distance is just employed to compare lay lengths measured in consecutive tests. The rope temperature, as an example, does not change the rope length significantly. Even in the presence of a temperature change from -25°C to $+25^{\circ}\text{C}$, the rope length would change of less than a part in 10^3 being the rope thermal expansion coefficient approximately of $10^{-5}/^{\circ}\text{C}$. As a consequence, in the case of the transport plant where the tests were carried out, the temperature change modifies the rope length of about 1 m. This distance error, although relevant in some applications, is here negligible since the lay length is obtained averaging the lay

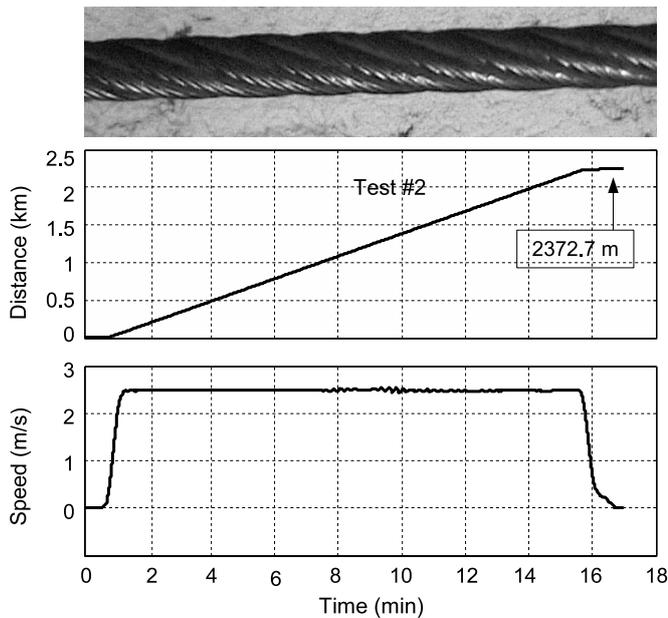


Fig. 10. Distance and rope speed obtained during the second test where the view angle was of about 20 cm (a rope frame is shown at the top) and the rope speed was of about 2.5 m/s.

measurements over a rope length of about 6 m.

V. CONCLUSIONS

A system for the automatic measurement of the rope lay length has been proposed and some results concerning a real transport plant have been presented. The system is based on a camera that continuously acquires running rope images. The images are processed off-line by means of an algorithm that extracts the rope contour of the rope images. The contour is processed with a fitting algorithm in order to extract the fundamental component whose period corresponds to an integer fraction of the rope lay length.

Simulation results carried out with a mathematical model of the rope contour have demonstrated the feasibility of the proposed method even when low resolution images are acquired. A criterium useful to set the optimal camera view angle has been also defined on the basis of the simulation results.

The phase information obtained from the fitting procedure has been employed to derive the distance covered by the rope during the test. In this way, the proposed vision system is an autonomous measurement system able to associate the information regarding the lay length at the rope position.

Tests performed by means of a general purpose camera on a working six-strands rope have been carried out at different rope speeds and at different camera view angles. The results are in agreement both with the simulations and with the measurements obtained with a traditional method.

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