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Wind Turbines Modeling as the Tool for Developing Algorithms of Processing their Video Recordings

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***Abstract*—In the real world, many factors exist disturbing observation of the examined phenomena and causing various noises and distortions in recorded signals. It very often makes it difficult or even impossible to optimize various signal processing algorithms, through finding appropriate parameters. In this paper, we show an application, that retrieves wind turbine rotor speed from recorded video. Next, we describe the process of reduction and construction of a paper wind turbine model with a particular emphasis on application to perform test video recordings. We made some recordings with that model and using them, we evaluate the accuracy of our software. Moreover, we evaluate the model itself, using motion magnification. Results show that this approach can be used for developing various wind turbine video processing algorithms.**

***Keywords*—Wind turbine, Image processing, Papercraft**

I. INTRODUCTION

Visual monitoring of wind turbines can supply much valuable information about their state, such as for example the rotational speed of rotors or rotors tilt angle. It is a relatively cheap method of surveillance, which doesn't demand any modifications inside the construction of a wind turbine and because of this fact, independent from internal sensors. It allows also present easily collected information, in an attractive and intuitive form, by applying extracted data directly in analyzed image.

Software development often requires an evaluation of various solutions in order to select the best one. To do this for software that automatically analyzes video, we need many recordings which include objects with already known parameters. In such a case, we can compare our results with the truth. However, in case of an image of the wind farm, it is very difficult without having very precise reference data. For example, the wind causes many quite unpredictable changes, like speed up or speed down of rotors. Moreover, other factors like lighting conditions often change parallelly, so sometimes it is impossible to evaluate which of them causes the differences in measurements.

In order to gain full control over the environmental factors, we can generate images by simulation. Unfortunately, despite huge progress in this field, still simulated objects often behave significantly different than the real ones. The study on modeling the aerodynamics of wind turbines presented in the literature [1] revealed discrepancies between model predictions and measurement results concerning the occurrence of dynamic stall onset over the rotor. Therefore, the results obtained by numerical models may not be as accurate as the real ones. One can take an effort to improve simulations to be more realistic, but it usually requires much more work and engaging high computational power, increasing the overall cost of such a project.

In this paper, we propose the use of paper models to make test recordings during the optimizing of video algorithms developed for turbine rotation frequency measurement. It is similar to simulation because we can place such a model inside a fully controlled, laboratory environment where we can tune up environmental conditions, like lighting, according to our needs. Simultaneously, an accurate projection of the reality is much easier than in the case of simulation. We can exploit natural properties of physical objects because models are subject to similar physical phenomena like the real ones. From that reason, a huge part of work which in case of simulation is made by man, in case of using model is provided by nature. Consequently, it allows obtaining realistic recordings with smaller costs.

II. PREVIOUS WORK

The main issue related to designing paper model is the unfolding problem. There are a few solutions to this problem. One of the most comprehensive and up to date review is included in the book [2].

In the paper [3] was proposed the automatic transformation of the computer 3D models into flat surfaces with utilizing numerical computations. This solution requires a little manual work but unfolded solids usually differ from the original. It is because a paper can't be bent simultaneously into two directions, thus such algorithms must get deal with it some way.

Another solution can be found in the literature [4], where authors proposed a whole system for creating dedicated 3D models to unfolding. It provides the possibility to manually decide how the shape will be divided into parts, that can bring better results than the first one. However, the system has some restrictions and not all the solids can be processed in such a way.

In our work, we adopted a method that relies on manually unfolding solids utilizing analytical formulas. It is described in the literature [5,6] for the application in paper models of ships.

Another problem is connecting paper parts with the moving mechanical ones. Some solutions to that issue were presented in [7].

III. Visual Tachometer

It is impossible to reproduce all the properties of the real object on the model. For that reason, we choose some which are the most important for testing our mechanisms. Our method for turbine frequency estimation is inspired by the literature [8]. A popular background subtraction method created by Bowden et al. [9] is used for that purpose,. It is a Gaussian Mixture-based method where each pixel is modeled by a mixture of K Gaussian distributions. The implementation is available in the OpenCV library. K was set to 5 by default.

The region of interest for each turbine can be manually selected. This should be a region that has an intersection with blades belonging to a single wind turbine, otherwise obtained results would be noisy. Therefore, we also implement a simple fully automatic mechanism which utilizes a contour detection algorithm described in [10]. We selected contour retrieval mode that retrieves only the extreme outer contours and contour approximation method that compresses horizontal, vertical, and diagonal segments and leaves only their endpoints. Fig. 1 presents an example of auto-selected regions of interest. In general, we found that placing the region of interest under or above the nacelle yields good results.

Figure 1. Manually selected regions of interest for wind turbines

For each selected region we count a number of “moving” pixels in consecutive timesteps. This allows us to obtain a histogram that can be further analyzed using Fast Fourier Transform (FFT) to obtain dominating frequencies of the signal. To obtain turbine rotation frequency the dominating frequency from the plot is divided by three (number of turbine blades) and multiplied by the number of frames per second (fps) of the recording.

The algorithm is composed of two main components: background subtraction (Fig. 2) and FFT algorithm (Fig. 3). The background subtraction algorithm accuracy for detecting turbine blades will change with the rotation angle of the wind turbine, i.e. when the wind turbine is perpendicular to the camera maximal accuracy should be obtained and when the turbine is in parallel, it probably will decrease significantly. Accuracy of the background subtraction method will also vary with different illumination conditions. On the other hand, the accuracy of the FFT algorithm depends on the number of timesteps we take into account. For 1024 timesteps and 30 fps the resolution of the method is equal to 0.009765625 Hz. For FFT algorithm we use fftpack module from scipy package.

To sum up, in order to test our software, we need a model, that allows us to record the same number and layout of “moving” pixels like a real turbine. To achieve this, we decided to reproduce the outer shape of the turbine, precisely.

Figure 2. Turbine blades are well recognized by background subtraction method except for the turbines in the far end

IV. Wind Turbine Environment

In real environmental conditions, we can observe high variations of wind speed over short periods of time. Previous research proved that wind turbine rotor speed and power output strongly depend on wind speed and its fluctuations [11]. Researchers develop numerical models of wind speed in order to simulate the complexity of the real world [12,13].

Fig. 4 presents observed wind speed and its impact on the generator shaft speed of experimental wind turbine [14], measured with an interval of 1 second. I order to obtain exact rotor speed in this turbine, we can divide generator shaft speed by a constant gear ratio which is equal to 29.95. Such a reference speed variations make it difficult to evaluate the precision of our software, so it is strongly desirable to eliminate this problem on the model in order to obtain stable rotor movements.

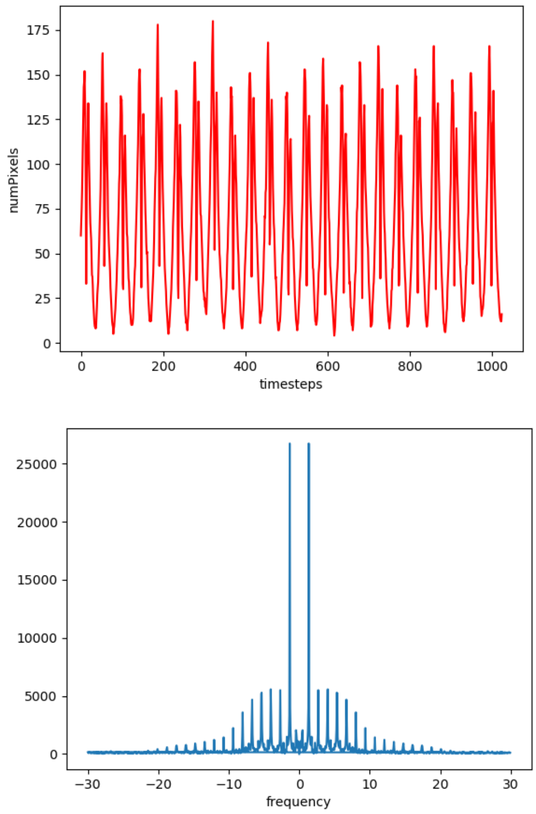

Figure 3. A number of moving pixels versus time (upper image) - it can be easily noticed when the wind blades intersect with the region of interest. We apply FFT to obtain a plot of dominating frequencies (bottom image).

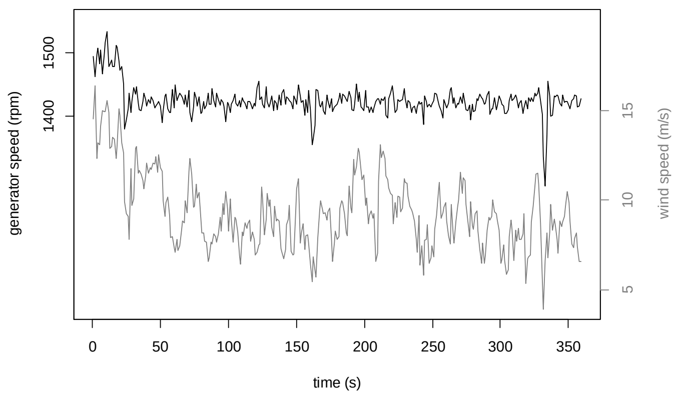

Figure 4. Measured wind speed and corresponding generator speed

V. Wind Turbine Model

In order to obtain the realistic shape of a wind turbine, we use as an example real one called Gamesa G87 with 78 m height tower [15,16]. Overall construction (Fig. 5), for simplicity, we divide between three independent parts, i.e., tower, nacelle, and rotor. What is different in our model from the real one, besides size and material, is that we are placed an engine instead of a generator in the nacelle. This is because we want to reach high stability during rotations of the rotor.

We used basic analytical geometry to obtain realistic solids shapes. Due to the natural physical properties of the model, we can obtain photorealistic dynamic shadows and lighting in recordings. In comparison, it is possible to obtain such results in simulation by utilizing ray tracing [17], but it is much more complex and computationally costly. Moreover, it requires a similar amount of manual work in order to create a virtual 3D model.

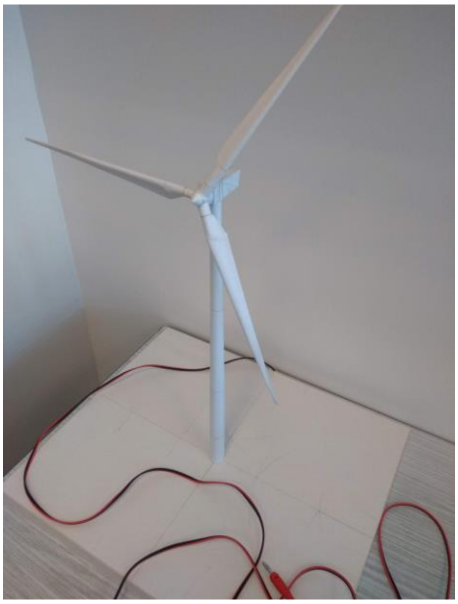

Figure 5. Finished model in 1:200 scale

A. Tower

The tower has a conical shape that consists of three similar steel modules, each one is placed upon another one. Each of them can be described by the three values, bottom outer diameter $ø_{kd}$, upper outer diameter $ø_{kg}$, and height h. Its intersection is shown in Fig. 6.

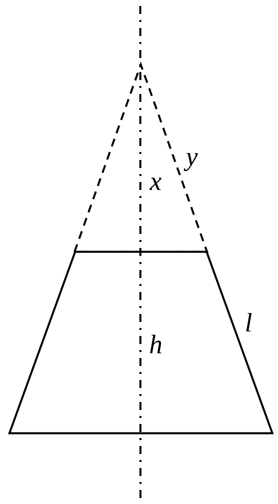

Figure 6. Tower module intersection

,In the model, each module consisted of three parts, two annuluses made from 1.2 mm thickness cardboard and side cover made from 0.25 mm thickness technical paper. The outer diameters of annuluses were calculated from the formula (1) where constant p = 0.5 mm is the double thickness of the used technical paper. Internal holes were left for power supply cables. .

$$ø_{\mathrm{w}} = ø_{\mathrm{k}} - p \tag{1}$$

The unfolded side cover is shown in Fig. 7. Marked values were calculated from the formulas (2), (3), (4) and (5):

$$x = \frac{h(ø_{wg}+p)}{ø_{wd}-ø_{wg}} \tag{2}$$

$$y = \sqrt{x^2 + \left(\tfrac{1}{2}(ø_{wg}+p)\right)^2} \tag{3}$$

$$l = \sqrt{(x+h)^2 + \left(\tfrac{1}{2}(ø_{wd}+p)\right)^2} - y \tag{4}$$

$$\alpha = \frac{180(ø_{wd}+p)}{y+l} \tag{5}$$

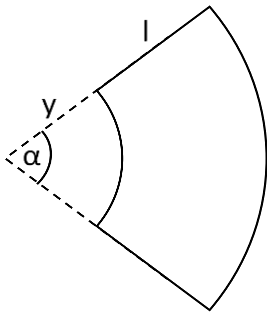

Figure 7. Unfolded tower module side cover

The whole tower for stability was placed on a cuboid base made from 1.2 mm thickness cardboard. The base has the same width as the rotor.

B. Nacelle

In this case, we are following a similar procedure like in case of the tower. The nacelle is some kind of prism. Its exact design was recovered from drawings. Moreover, we use basic dimensions, i.e. length, height, and width. Inside was installed a metal gearmotor. The whole element was made from technical paper without additional reinforcements.

C. Rotor

This is the most complicated part of the model, although again we are following the similar procedure like before. The overall element consists of the hub and three blades. We build it all from technical paper with, in this case, additional reinforcements made from 1.2 mm thickness cardboard.

VI. Experiment

The experiment consisted of two stages. Firstly, we evaluate the model itself. To do this, we placed a laser tachometer before rotor and next, we set the desirable voltage on the power supply. Then, we measure rotor rotational speed. This routine was repeated for voltages equal to 3 V, 4.5 V, 6 V and 9 V.

Moreover, we have placed a camera next to the nacelle, in order to evaluate the robustness of this important element. We applied phase-based Eulerian motion magnification algorithms known in the literature [18] on the obtained recordings to catch small undesirable movements of the construction. The method uses sophisticated image processing algorithms, such as complex steerable pyramids in order to compute the local phase variations in order to measure motion and to perform temporal processing to amplify motion in selected temporal frequency bands. Each frame of the video was processed and small differences between frames, invisible for the naked eye, was uncovered. In order to amplify only desirable movements and to prevent noise intensification, we amplify movements only in a narrow bandwidth.

Secondly, we set constant rotational speed and we perform two sequences of camera recordings. During each one, the camera was placed in different distance z. In a different recording session, we checked how an angle β between camera recording surface and rotor rotation surface influence on measurements precision. We tested angles equals to 0, 30, 45, 60 degrees (Fig. 9). Bottom view on the whole stand is shown in Fig. 8. We also tested two different framerates and two different resolutions.

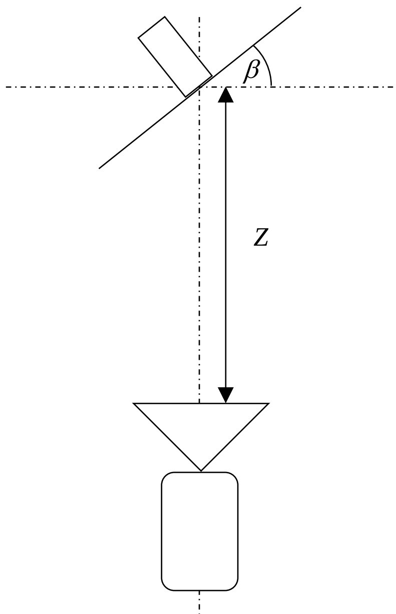

Figure 8. Measurement stand

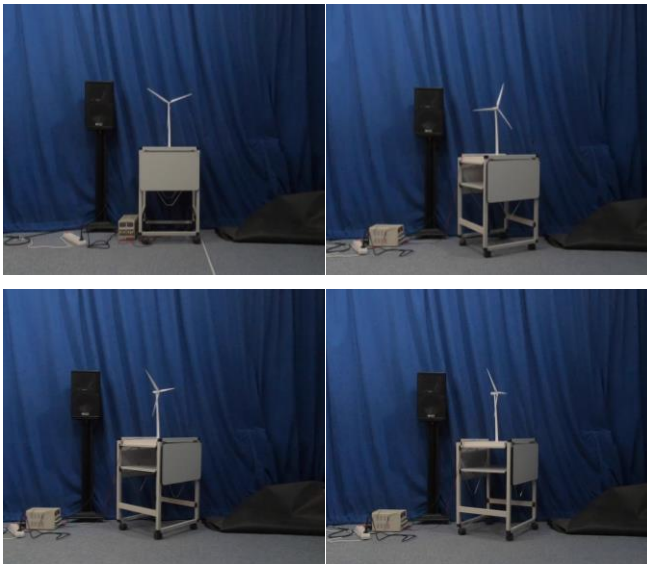

Figure 9. Wind turbine model recorded from 4 different angles

VII. RESULTS

Result description is divided into two sections, according to the experiment. The first part is connected with model evaluation itself, where the second one shows if the created model is useful for software testing.

A. *Model evaluation*

Table 1 shows speeds depending on the voltage. There are arithmetic means of five measurements. We observed that the model covers the whole range of rotational speeds achieved by the real wind turbine.

TABLE I. SPEEDS REACHED BY THE MODEL

Voltage [V]	3	4.5	6	9
Speed [rpm]	6.5	9.9	12.9	20.0

The video transformed by recalled in section V phase-based Eulerian motion magnification [18] has shown that the whole robustness of nacelle is insufficient, and the front part of the floor is bent by the forces from the rotations of the rotor. The problem was illustrated on Fig. 10 and Fig. 11. In order to achieve these results, we amplify the motions in the band from 0.64 Hz to 0.65 Hz. We choose that band because we want to amplify motions in frequency three times greater than the rotor rotational frequency. This is because the rotor achieve each position three times during full rotation.

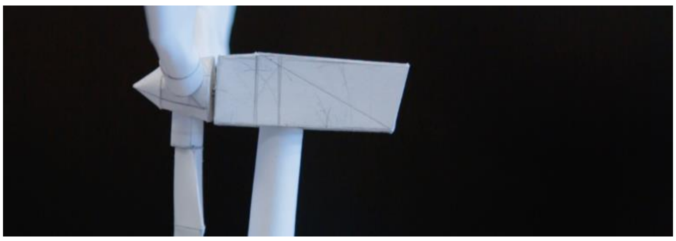

Figure 10. Original video frame from the camera

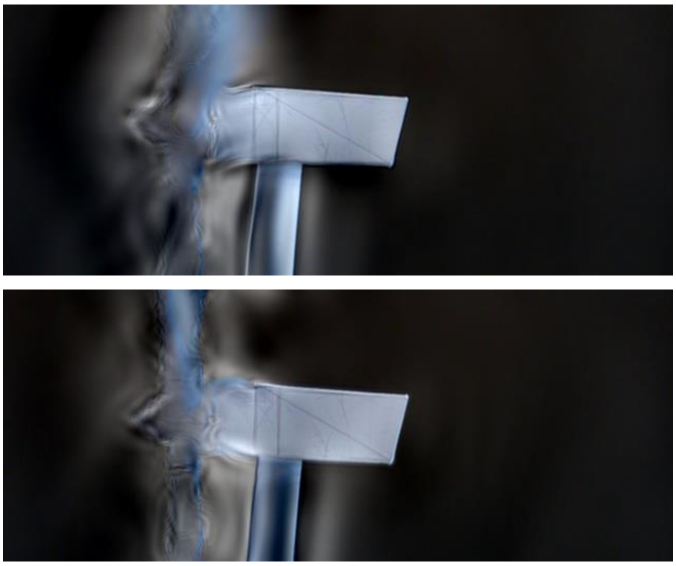

Figure 11. Two separate frames after motion magnification. Visible movements in the front part of the nacelle floor

B. *Visual tachometer evaluation*

Table 2 shows the results for different angles between rotor and camera. The distance of the recording was 3 m, which in reality is 600 m. The resolution was 1920x1080 px and the framerate was 60 fps. The reference speed was 12.9 rpm. We can observe that the achieved precision is independent on the angle.

TABLE II. MEASURED SPEEDS ACCORDING TO ANGLE

Angle [°]	0	30	45	60
Speed [rpm]	14.0	14.0	14.0	14.0

Further, in Table 3 and Table, 4 were shown results with different camera settings. During this test, the recording was taken from 1.5 m distance. We noticed that for higher framerates, the measurement was becoming less accurate. Moreover, we noticed some benefits from the increase of the resolution, but only in the case of in smaller frame rate.

TABLE III. MEASURED SPEEDS IN 1920X1080 PX RESOLUTION

Framerate [fps]	30	60
Speed [rpm]	12.9	14.0

TABLE IV. MEASURED SPEEDS IN 640X360 PX RESOLUTION

Framerate [fps]	30	60
Speed [rpm]	13.1	13.9

The recordings of the model were made with GoPro Hero 6 camera, which is small and portable. However, the main disadvantage of this device is automatic control of such parameters as exposure time. Therefore, the results obtained by our method depend on the camera settings. In the one case, i.e. 1920x1080 resolution with 30 frames per second, we obtained the same result as the ground truth. We can quickly notice it, thanks to measurements on the model. If we used only computer simulation, we would not use a camera, so it is impossible to observe such differences. Further experiments will be provided in order to improve the algorithm results and optimize image acquisition.

VIII. CONCLUSIONS

In this paper, we presented the working model of a wind turbine reconstructed in laboratory conditions. We also showed a sample application to generate test recordings for our developed visual tachometer. Despite the simplicity, our solution has several advantages. Firstly, it allows for generating almost any test videos which can cover quite many scenarios of using the tachometer software. Secondly, it helps in results interpretation by utilization of fully controlled laboratory environment. It guarantees that only one parameter changes in turn and moreover it supplies a stable reference point for measurements. Thanks to the detailed preservation of the scale in the model, on image sensors we can record virtually identical image like in case of reality if we keep the right distances between the camera and the model. So, by our method, we can test not only software but also hardware like cameras with various settings. This decreases the risk of failures during deployment of the whole system. It also makes software development team independent from the access to the wind farms, which enables faster and more effective experimenting.

Moreover, in this work we have shown some methods of paper model evaluation. Motion magnification algorithms can provide quick insight onto problems with model robustness. It is economical in case of the model-based approach because making the model is inexpensive, thus, in this case, simulations and other computationally costly methods are not necessary. Because constructing iteratively several copies to find the optimal solution is possible and quite easy, despite the development and popularity of computer simulation techniques, hardware scaled model are still in use.

There are many ways that the presented model can be improved since we have found that its robustness is not fully satisfying in some respects, thus it is possible to make additional reinforcements to solve this problem. For example, the whole solid of the model can be improved in order to become more realistic by the removal of some undesirable tensions, that is caused by water-based glue.

Last but not least, we see also a potential for further research on the proposed algorithm. It is still an open question, how short can last the measuring of the time. Currently, we assume that 30 seconds will be sufficient to obtain the same result as a reference value, and this assumption was fulfilled, indeed. In the future, using our method, we can also check our algorithm against dynamic changes in the rotation speed, thanks to engine control abilities. Finally, a challenging task to be solved is making the algorithm more robust against environmental conditions such as lighting variations.

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REFERENCES

[1] J. G. Leishman, Challenges in modelling the unsteady aerodynamics of wind turbines, Wind Energy 5 (2-3), pp. 85-132, 2002

[2] D. Guzmán, Fundamentals of Paper Model Design, Mi Casa Publishing, Puerto Rico, 2010

[3] F. Massarwi, C. Gotsman, G. Elber, Paper-craft from 3D polygonal models using generalized cylinders, Computer Aided Geometric Design, Vol. 25, pp. 576–591, 2008

[4] P. Paczkowski, J. Dorsey, H. Rushmeier, M.H. Kim, PaperCraft3D: Paper-Based 3D Modeling and Scene Fabrication, IEEE Transactions on Visualization and Computer Graphics, Vol. 25, No. 4, April 2019.

[5] A. Samek, Designing paper models of ships. Projektowanie papierowych modeli okrętów, Liga Przyjaciół Żołnierza, 1956 (in Polish)

[6] A. Karpiński, S. Smolis, Paper models of ships and ships .Modele kartonowe statków i okrętów, Wydawnictwo Komunikacji i Łączności, 1983 (in Polish)

[7] H. Oh, From Papercraft to Paper Mechatronics: Exploring a New Medium and Developing a Computational Design Tool, Adjunct Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology, New York, NY, USA, pp. 17-20, 2015

[8] C. López, J. Blanes, R. González, L. Sánchez, Wind turbine angular frequency analysis by means of computer vision techniques, Renewable Energy 33(12), pp. 2799-2803, 2010

[9] P. KaewTraKulPong and R. Bowden, “An improved adaptive background mixture model for real-time tracking with shadow detection,” inVideo-based surveillance systems. Springer, 2002, pp. 135–144.

[10] S. Suzuki, K. Abe, Topological Structural Analysis of Digitized Binary Images by Border Following, Computer Vision, Graphics, and Image Processing, vol. 30, no. 1, pp 32-46, 1985

[11] E. Welfonder, R. Neifer, M. Spanner, “Development and experimental identification of dynamic models for wind turbines,” Contr. Eng. Practice, vol. 5, no. 1, pp. 63–73, 1997

[12] C. Nichita, D. Luca, B. Dakyo, E. Ceanga, “Large band simulation of the wind speed for real-time wind turbine simulators,” IEEE Transactions on Energy Conversion, vol. 17, no. 4, pp. 523-529, Dec. 2002

[13] A. Naimo, “A Novel Approach to Generate Synthetic Wind Data,” Procedia - Social and Behavioral Sciences, Vol. 108, pp. 187-196, 2014

[14] Z. Krzeminski, J. Szewczyk, E. Bogalecka, Small wind turbine control system with a stall effect. Przeglad Elektrotechniczny 94(5), pp. 104-111, 2018

[15] Gamesa Eólica, G87-2.0 MW, https://www.edprnorthamerica.com/wp-content/uploads/2014/04/G87.pdf, 2004

[16] A. Bjorck, Coordinates and calculations for the FFA-Wl-xxx, FFA-W2-xxx and FFA-W3-xxx series of airfoils for horizontal axis wind turbines, Stockholm: The Aeronautical Research Institute of Sweden, 1990

[17] S. Parker, H. Friedrich, D. Luebke, K. Morley, J. Bigler, J. Hoberock, D. McAllister, A. Robison, A. Dietrich, G. Humphreys, M. McGuire, M. Stich, GPU Ray Tracing, Communications of the ACM, vol. 56, no. 5, pp. 93-101, 2013

[18] N. Wadhwa, M. Rubinstein, F. Durand, W. T. Freeman, Phase-Based Video Motion Processing, ACM Transactions on Graphics, Vol. 32, No. 4, July 2013