MODEL BASED WIND VECTOR FIELD RECONSTRUCTION FROM LIDAR DATA

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Summary

In recent years lidar technology found its way into wind energy for resource assessment and control. For both fields of application it is crucial to reconstruct the wind field from the limited information provided by a lidar system. For lidar assisted wind turbine control model based wind field reconstruction is used to obtain signals from wind characteristics such as wind speed, direction and shears in a high temporal resolution. This work shows how these methods can be used for lidar based wind resource assessment in complex situations, where high accuracy is important, but cannot be archived by conventional technique. The reconstruction is validated for ground based lidar systems with measurement data and for floating lidar systems with detailed simulations.

1. Introduction

Lidar (light detection and ranging) systems for site assessment in flat terrain have been established over the last years and show good correlation with met masts based on $10\ \mathrm{min}$ averages [1]. However, lidar systems in complex terrain and offshore on floating platforms show problems and solving them is still a subject of current research ([2], [3]). Another field of investigation is lidar assisted wind turbine control. For this purpose model based approaches are used ([4], [5]) to calculate signals such as wind speed, direction and shears. Lidar measurements and the wind field are modeled and then identified similar to the observer design method used in control theory. First field tests [6] show that with these methods nacelle based lidar systems are able to provide signals with good correlations in the range of $10\ \mathrm{s}$, which can be used in real time to improve collective pitch control.

This paper examines the extension of the model based wind field reconstruction for ground based and floating lidar systems. The conventional reconstruction methods used by commercial lidar systems also use an internal wind model (homogeneous flow). Therefore, the intention of this work is not to propose a totally new approach, but provide a system theoretical view on wind reconstruction which can be useful to improve the lidar measurements in situations, where the conventional technique fails.

2. Basic Idea

The basic idea of model based wind field reconstruction is to retrieve useful information on the wind from the lidar measurements depending on the application. But this system theoretical view also gives a framework to evaluate and optimize the level and the reliability of the reconstructed wind information, which will be explained in this section.

A lidar system can be regarded in a system theoretical way (see Figure 1): All known settings such as the scan trajectory can be considered as inputs to the system. All unknown influences to the measurements are the disturbances and the measurements themselves are the outputs of the system. In system theory [7] a disturbance observer can be used to reconstruct the disturbances from the system in- and outputs, if observability is given. Robustness evaluates, how well this is done in the presence of model and measurement uncertainties. Whereas observability and robustness for dynamic systems are complex, for static systems they can be simplified to the questions, whether a unique disturbance can be found which caused the measured output with given input and how sensible it is for uncertainties. For this purpose, a model of the system (analytically or CFD) is needed, similar to a simulation model and the observation can be considered to be inverse to a simulation.

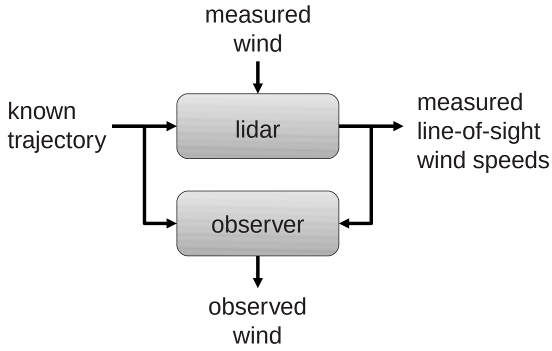

Figure 1: System theoretical view on lidar measurements and wind field reconstruction.

A lidar located in $[x_0\ y_0\ z_0]$ measuring in point i can be simulated by

$$v_{los,i} = l_{xi}u_i + l_{yi}v_i + l_{zi}w_i, \tag{1}$$

which is a projection of the local wind vector $[u_i\ v_i\ w_i]$ and the normalized vector of the laser beam focusing in the point $[x_i\ y_i\ z_i]$ with a focus length f_i:

$$\begin{bmatrix} l_{xi} \\ l_{yi} \\ l_{zi} \end{bmatrix} = \frac{1}{f_i} \begin{bmatrix} x_i - x_0 \\ y_i - y_0 \\ z_i - z_0 \end{bmatrix}. \tag{2}$$

Since there is only one equation for three unknowns, it is impossible to reconstruct the local wind vector from $v_{los,i}$. Observability can be restored by changing the wind model, e.g. it can be assumed, that the wind vector in 3 measurement points is the same, which yields 3 equations for 3 unknowns. The wind model has to be chosen according to the application and the quality of the results depends on the validity of the model. In the following sections this will be illustrated by the application of this basic idea to ground based and floating lidar systems.

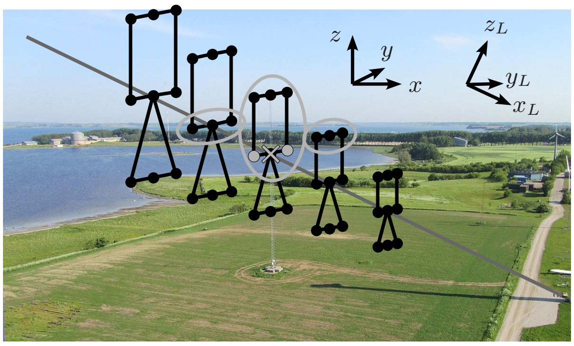

Figure 2: Measurement campaign at Risø Campus. The wind vector in the center (cross) is reconstructed using the measurement in the points marked with gray dots for 3.1 or inside the circles for 3.2.

3. Application to Ground Based Lidars

In this first example a scanning lidar system [8] was installed at the Risø Campus tilted by $\Theta_L = 25\,\mathrm{deg}$, scanning the wind circulating around a met mast, see Figure 2, with a 3x3 grid trajectory on 5 horizontal planes within $2\,\mathrm{s}$. The center points of the third focus distance were located close to the ultrasonic anemometers installed on the met mast. For the following investigations all data sets are used, including low wind speeds and wind directions orthogonal to the main measurement direction.

3.1. Reconstruction in Flat Terrain

If the tilt angle is known, the wind can be reconstructed in the $[x\ y\ z]$ coordinate system, assuming that the wind is homogeneous in planes parallel to the ground. Furthermore, it is assumed that the vertical wind w can be neglected. This simple wind model can be combined with the simple lidar measurement model (1) and the line-of-sight wind speeds of the two points next to the center anemometer could be simulated by

$$\underbrace{\begin{bmatrix} v_{los,1} \\ \vdots \\ v_{los,n} \end{bmatrix}}_{m} = \underbrace{\begin{bmatrix} \frac{x_1}{f_1} & \frac{y_1}{f_1} & \frac{z_1}{f_1} \\ \vdots & \vdots & \vdots \\ \frac{x_n}{f_n} & \frac{y_n}{f_n} & \frac{z_n}{f_n} \end{bmatrix}}_{A} \underbrace{\begin{bmatrix} u \\ v \\ w \end{bmatrix}}_{s}. \quad (3)$$

In the 2D case of real measurements the wind can be reconstructed simply by a matrix inversion

$$\begin{bmatrix} u \\ v \end{bmatrix} = A^{-1} \begin{bmatrix} v_{los,1} \\ v_{los,2} \end{bmatrix}. \quad (4)$$

This simple example shows why observations can be considered to be inverse to simulations and that circular or arc scans normally used for lidar measurements are not necessary. Figure 3 depicts better correlation with the sonic anemometer on the met mast for u compared to v. This is due to the higher values in the second line of A^{-1} and thus measurement errors in the line-of-sight wind speeds have more effect on v. An appropriate measure for robustness can be defined in the following way: The condition number of A describes the worst case factor which transfers relative errors from measurement vector m to the searched vector s. This approach can be used to optimize the setup of lidar measurements: in this case the condition number could have been reduced from 5.23 to 1, by approaching the lidar to the met mast, setting $x_1 = x_2 = y_1 = -y_2$.

3.2. Reconstruction in Complex Terrain

The investigation above used the knowledge of the tilt angle Θ_L and assumed that the flow is parallel to the ground. In complex terrain this assumption is not always useful: e.g. the wind will be parallel to a linear slope at lower heights, but parallel to the surface of the earth at higher heights. Due to the vertical shear the results of conventional reconstruction methods will change for the worse.

In a further investigation the knowledge of the tilt angle is not used and the wind is reconstructed in the $[x_L\ y_L\ z_L]$ coordinate system, by including the vertical wind shear in the wind model. Using more than one focus distance to distinguish between shears and inflow angles was proposed in [4] and tested in simulations in [5], ignoring the drift of the shear due to the flow angle. Therefore, the five parameter model from [4] is modified. First, the wind measured in point i is defined as

$$u_{Wi} = v_0 + \delta_H y_{Wi} + \delta_V z_{Wi}, \quad (5)$$

where v_0 is the wind speed in the origin and δ_V the vertical and δ_H the horizontal shear. The wind coordinates $[x_{Wi}\ y_{Wi}\ z_{Wi}]$ can be transformed to the lidar coordinate system by a rotation of the horizontal and vertical inflow angle, α_H and α_V. With a given set of v_0, α_H, α_V, δ_H, δ_V the coordinates of the measurements can be transformed to the wind coordinates and the line-of-sight wind speed can be simulated by

$$v_{los,i} = \frac{x_{Wi}}{f_i} u_{Wi}. \quad (6)$$

This simulation model again can be used to estimate the five parameters using the measured $v_{los,i}$. A numerical inversion for the nonlinear equations can be achieved by solving the least-squares minimization problem

$$\min_{v_0,\alpha_H,\alpha_V,\delta_H,\delta_V} \sum_{i=1}^{n} \left(v_{los,i} - \frac{x_{Wi}}{f_i} u_{Wi} \right)^2, \quad (7)$$

and the wind vector in lidar coordinates can be calculated with (5) and the inverse transformation. The linear model (3) which only accounts for the sloped inflow and the nonlinear model neglecting δ_H are applied to the data using $n = 12$ points (see Figure 2), both using the least squares method. The coefficient of determination can be improved from $R^2 = 0.666$ to 0.943 for the w component. The results from Figure 3 show, that it is possible to enhance the measurement of the 3D wind vector in the presence of vertical shear, but it is necessary to investigate under which conditions observability is given and how higher robustness can be obtained.

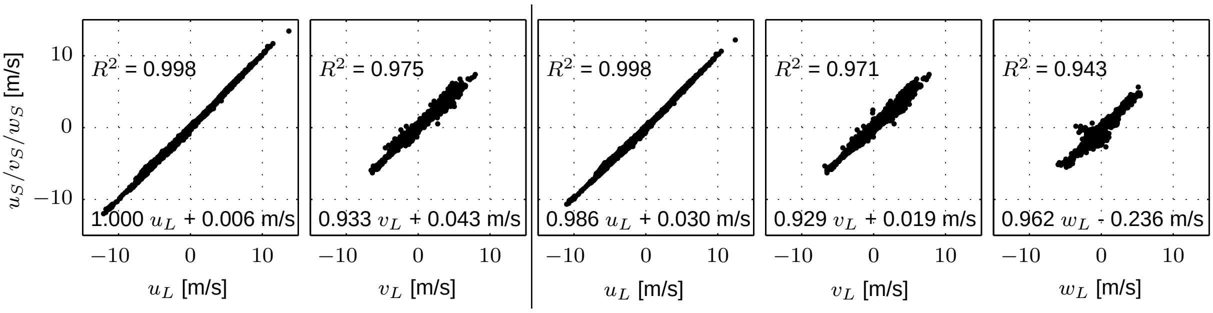

Figure 3: Regression between lidar and sonic anemometer for the linear (left) and the nonlinear model (right).

4. Application to Floating Lidars

Floating lidars are a promising option to replace expensive floating met masts for the evaluation of offshore wind resources. The wave motion disturbs the measurement, which is why several attempts have been made to compensate the effect either by stabilization of the floating platform with active or passive hardware solutions or by software solutions [3].

Here, a software solution is proposed, which uses the model based wind field reconstruction approach. For this purpose, the floating lidar is first simulated.

The wave height η is according to the Airy wave theory:

$$\eta(x,t) = \frac{H}{2}\cos(kx - \omega t), \qquad (8)$$

where H is the wave peak-to-peak amplitude, k the angular wavenumber and $\omega = \frac{2\pi}{T_p}$ the angular frequency, depending on the wave period T_p. For deep water, wavenumber and frequency are connected by the acceleration due to gravity $g = \frac{\omega^2}{k}$. For this investigation $T_p = 5$ s and $H = 4$ m are chosen.

In a simplified simulation it is assumed that the floating platform follows the wave surface ($z_0 = \eta$) and is only able to change its vertical position ($x_0 = y_0 = 0$ m), resulting in two degrees of freedom (DOF) out of six.

Hence, for the pitch angle Θ_L (rotation around y axis) of the floating lidar following the wave surface it holds:

$$\tan(\Theta_L(x,t)) = -\frac{Hk}{2}\sin(kx - \omega t). \qquad (9)$$

To simulate the measurement of the floating lidar system, the lidar coordinates have to be transformed to the inertial system:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = T_{pitch}(\Theta_L)\begin{bmatrix} x_L \\ y_L \\ z_L \end{bmatrix} + \begin{bmatrix} x_0 \\ y_0 \\ z_0 \end{bmatrix}. \qquad (10)$$

With a hydrodynamic simulation the missing translational and rotational degrees of freedom can be considered in a similar way.

For this investigation a continuous-wave lidar is simulated, focusing in $z_L = 100$ m and measuring in 50 points per second on a circular scan with a half opening angle of 30 deg. Figure 4 shows the measurement path of the focus point during one wave period, using (10). By scanning a three dimensional wind field (u, v, w over t, y, z) and using Taylor's frozen turbulence hypothesis (connecting x and t), the line-of-sight wind speeds can be calculated with (1).

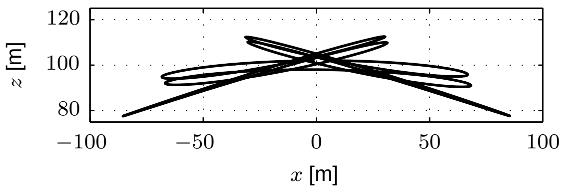

Figure 4: Path of the focus point due to waves.

4.1. Constant Wind

In the first simulation a constant wind of $u = 10$ m/s at 100 m and a vertical shear of $\delta_V = 0.05$ 1/s is used. Conventional VAD technique assumes the 3D wind vector to be constant over the last full circle and uses the least squares method to fit the line-of-sight wind speeds to a sinus curve, which for a circular scan is mathematically equivalent to using (3). Figure 5 shows, that the conventional wind reconstruction has a periodic error, leading to an underestimation of 6%. This description of the VAD technique in coordinates rather than in trigonometry shows the problem and guides to a solution: conventional wind reconstruction uses the non-transformed lidar coordinates and thus is not inverse to the simulation and not able to find a correct solution (see Figure 5). Furthermore, due to the non-linearity of the movement, more measurements are done below 100 m (see Figure 4). Therefore, the nonlinear model (5) with the wind speed v_0, the vertical shear δ_V and the wind direction α_H is used for the reconstruction. Furthermore, it is assumed, that in a perfect case the inclination Θ_L and the heave z_0 can be measured, to correct the lidar coordinates and in the more realistic case, that only Θ_L can be measured. Figure 5 depicts that in the perfect case there is no error, due to the perfect inversion. If only Θ_L can be measured, there is a periodic, zero-mean error.

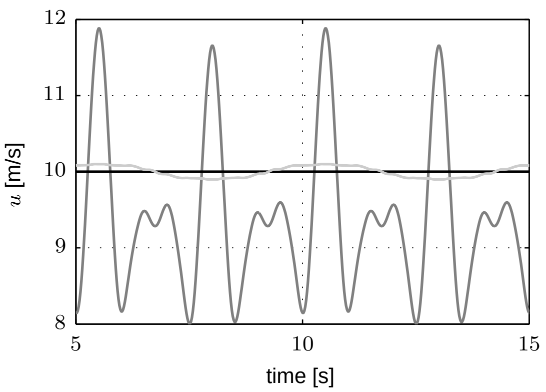

Figure 5: Reconstruction of constant wind speed: common technique (dark gray); nonlinear model with inclination information (light gray) and additional heave information (black).

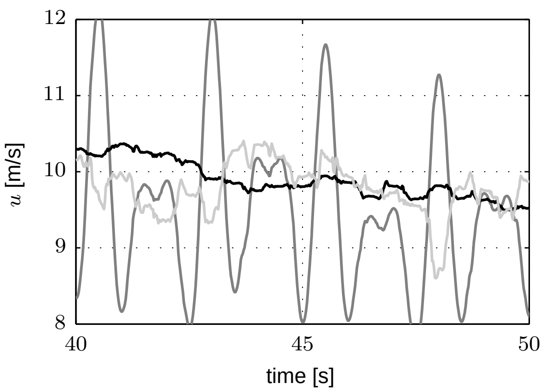

Figure 6: Reconstruction of turbulent wind speed: common technique (dark gray); nonlinear model with inclination information (light gray) and fixed lidar (black).

4.2. Turbulent Wind

In a second simulation a turbulent wind field with a mean wind of $10\ \mathrm{m/s}$, a turbulence intensity of 21% and a IEC-conform shear for offshore conditions is used. Furthermore, a continous wave weighting function [9] is applied. As a reference the wind field is also scanned with no waves. In Figure 6 it can be seen that the conventional reconstruction still has a non-zero-mean error (-2.98% over the $10\ \mathrm{min}$ simulation), while the model based reconstruction methods are closer to the fixed lidar independend from whether the heave information is considered or not. In total they only have an error of 0.05% and 0.04%.

5. Conclusion

In this work a system-theoretical view on wind field reconstruction for site assessment based on lidar measurements is given. Conventional technique uses the same wind model in all situations, which causes problems in complex terrain or on floating platforms, although detailed simulation models exist. These models can be used for wind reconstruction, if they can be inverted with a unique solution.
The methods are first evaluated with real measurements for a ground based lidar: By including a more detailed model, the reconstruction of the wind vector can be significantly improved. Secondly, the model based approach is applied to floating lidar simulations: By including the inclination information and the vertical shear into the model, the measurement error caused by the motion can be compensated.

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References

[1] Clifton, A., Elliott, D., and Courtney, M., “Recommended practices for remote sensing for wind energy applications,” Tech. rep., 2012.

[2] Bradley, S., Perrott, Y., Behrens, P., and Oldroyd, A., “Corrections for Wind-Speed Errors from Sodar and Lidar in Complex Terrain,” *Boundary-Layer Meteorology*, Vol. 143, 2012, pp. 37–48.

[3] Gottschall, J., Lilov, H., Wolken-Möhlmann, G., and Lange, B., “Lidars on floating offshore platforms,” *EWEA*, Copenhagen, Denmark, 2012.

[4] Schlipf, D., Kapp, S., Anger, J., Bischoff, O., Hofsäß, M., Rettenmeier, A., Smolka, U., and Kühn, M., “Prospects of Optimization of Energy Production by LiDAR Assisted Control of Wind Turbines,” *EWEA*, Brussels, Belgium, 2011.

[5] Kapp, S. and Kühn, M., “A Five-Parameter Wind Field Estimation Method Based on Spherical Upwind Lidar Measurements,” *TORQUE*, Oldenburg, Germany, 2012.

[6] Schlipf, D., Fleming, P., Haizmann, F., Scholbrock, A., Hofsäß, M., Wright, A., and Cheng, P. W., “Field Testing of Feedforward Collective Pitch Control on the CART2 Using a Nacelle-Based Lidar Scanner,” *TORQUE*, Oldenburg, Germany, 2012.

[7] Lunze, J., *Regelungstechnik 2*, Springer, Berlin, Germany, 2010.

[8] Rettenmeier, A., Bischoff, O., Hofsäß, M., Schlipf, D., Trujillo, J. J., and Kühn, M., “Wind field analyses using a nacelle-based LIDAR system,” *EWEC*, Warsaw, Poland, 2010.

[9] Simley, E., Pao, L. Y., Frehlich, R., Jonkman, B., and Kelley, N., “Analysis of Wind Speed Measurements using Continuous Wave LIDAR for Wind Turbine Control,” *AIAA*, Orlando, USA, 2011.