# Reconstruction of Wind Turbine Blade Geometry and Internal Structure from Point Cloud Data

Benjamin Tasistro-Hart[1]; Tristan Al-Haddad[2]; Lawrence C. Bank[3]; and Russell Gentry[4]

[1]Georgia Institute of Technology, School of Architecture, 145 4th St. NW, Atlanta, GA 30332. E-mail: btasistrohart@gatech.edu
[2]Georgia Institute of Technology, School of Architecture, 145 4th St. NW, Atlanta, GA 30332. E-mail: tristan.al-haddad@design.gatech.edu
[3]City College of New York, 160 Convent Ave., NY 10031, New York. E-mail: lbank2@ccny.cuny.edu
[4]Georgia Institute of Technology, School of Architecture, 145 4th St. NW, Atlanta, GA 30332. E-mail: russell.gentry@design.gatech.edu

## ABSTRACT

This paper presents a method for the digital reconstruction of the geometry of a wind turbine blade from a point-cloud model to polysurface model. The digital reconstruction of the blade geometry is needed to develop computer models that can be used by architects and engineers to design and analyze blade parts for reuse and recycling of decommissioned wind turbine blades. Initial studies of wind-blade geometry led to the creation of an airfoil database that stores the normalized coordinates of publicly-available airfoil profiles. A workflow was developed in which these airfoil profiles are best-fitted to targeted cross-sections of point-cloud representations of a blade. The method for best-fitting airfoil curves is optimized by minimizing the distance between points sampled on the curve and point-cloud cross section. To demonstrate the workflow, a digitally-created point-cloud model of a 100 m blade developed by Sandia National Laboratory was used to test the reconstruction routine.

## INTRODUCTION

The production of wind energy worldwide has increased twenty-fold since 2001 (GWEC). Almost all this energy is generated by three-bladed wind turbines with fiber reinforced polymer (aka plastic) (FRP) composite wind blades. Blades for turbines installed in the early 2000s are nearing the end of their 20- year design lives, and the need to recycle the blades has become a well-recognized problem (Albers et al. 2009; Jensen and Skelton, 2018). In addition, many wind farm sites are being re-powered, with new and more powerful turbines and blade sets being installed even though the current turbines have not reached their design lives. Advancements in turbine technology have rendered these turbines functionally obsolete (Delony 2018). Recycling of the steel and copper that make up most of the turbine mass is well understood, but the potential for recycling or re-purposing the composite materials has not been addressed (Liu and Barlow 2017).

Most blades are constructed from thermoset composites using mostly glass but some carbon fibers (Mishnaevsky et al. 2017). Currently material is recycled by shredding the blades, and the shredded polymer composite material is utilized as partial replacement for coal or natural gas in fossil power plants and the ash for feedstock in cement kilns (Job 2013). Efforts to use the ground waste in the production of new FRP composites shows that the inclusion of recycled materials dramatically decreases the mechanical properties of the material (Beauson et al. 2016). Chemical and thermal methods are also being investigated. For a review of FRP composite recycling methods see Oliveux et al (2015). Given this context, our research program seeks to develop re-use applications for wind blades, aiming to use entire blades or large parts of blades in architectural and civil infrastructure applications, taking advantage of their structural properties (see www.re-wind.info).

## WIND BLADE GEOMETRY

Wind blades range from 9 m to 90 m in length. They are essentially large propellers, whose exterior surface is created by a series of successively more aerodynamic profiles placed along a reference axis. Beginning at the root, a circular section (about 10% of the total length) blends into a series of airfoil sections which taper along their length (about 90% of the total length). Each profile is located at a specific point away from the start point of the reference axis and provides material information regarding the layering of the composites and cores as well as geometric information (Fig. 1) that describes the shape the blade at that point (Bronsted et. al 2005). Structural loading and aerodynamic performance have an inverse relationship (Fig.2) along the length of the blade where the root and transitional region have poor aerodynamic performance but carry the highest structural loads while the mid-span and tip have a maximized lift-to-drag ratio and carry less structural loads (Schubel 2012). Wind blades behave as huge cantilevers, with the primary bending moments carried by a tapering and twisting box beam consisting of spar caps (i.e., flanges) bounded by internal structural webs (Fig. 3) that are also composed of sandwich panels (Gentry et al. 2018).

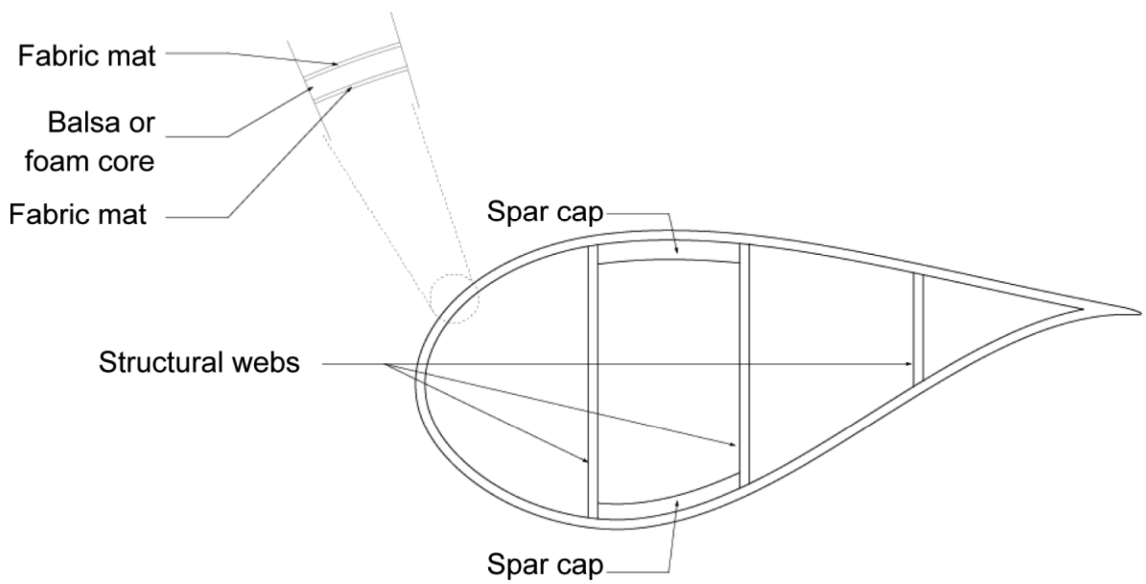


**Figure 1. Schematic cross-section of wind blade.**

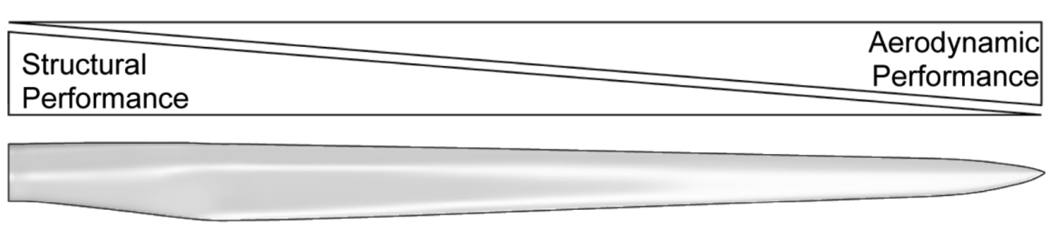


**Figure 2. Structural performance vs. aerodynamic performance along length of blade.**

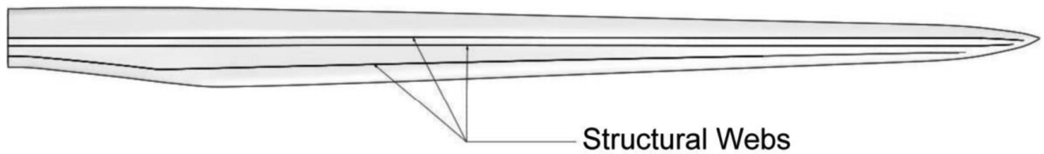


**Figure 3. Internal structural webs of wind blade.**


**Figure 4. Interfaces of NuMAD wind blade design software displaying key geometric parameters offset (Arias, 2016; Griffith and Ashwill 2011)**

Most of the information regarding the geometric and material properties of wind blades is the intellectual property of the blade designers and manufacturers. However, some of this data can be acquired using 3D non-contact metrology. These methods are of interest in the re-use context because of low-cost variants, such as photogrammetry, laser scanning, and LIDAR can provide detailed point-cloud models that can be used in robot path planning. In addition, these models do not infringe on proprietary rights of the original manufacturers (Siddiqi 2018). Architects and engineers who work with renovation or retrofitting often use 3D non-contact metrology methods to create a detailed point-cloud model as starting point of a project. Much research has been conducted on developing automated workflows which translate point-cloud models into integrated volumetric building models which allow for the necessary flexibility in the design process (Ochmann 2015).

## WIND BLADE GEOMETRY RECONSTRUCTION

Software routines that build representative models of wind blades within CAD packages commonly used by architects and engineers have been developed (Charalampous et al. 2015). In this paper, the reconstruction of the wind blade geometry involves the use of an evolutionary solver to create the complex exterior surfaces from a point-cloud. The resulting blade model is represented as airfoils at stations along the blade length, in manner analogous to the process used in the Numerical Manufacturing and Design Tool (NuMAD), a wind blade design tool developed by Sandia National Laboratory (Berg and Resor 2012). The use of NuMAD for the design of wind blades, and the implementation of evolutionary solvers in modern CAD packages is well-documented (Arias 2016; Rutten 2010). Both methods will be described briefly below.

**Numerical Manufacturing and Design Tool (NuMAD):** Developed by Sandia National Laboratory, NuMAD facilitates the structural design of wind blades. In NuMAD, wind blades are modelled as a series of closed section curves at set intervals, termed stations, along a reference axis that describe the outer geometry of the wind blade and provide reference points for the internal geometry. At each station, the user specifies a variety of geometric parameters, such as, the airfoil type, distance from root, chord length, twist (rotation) of station and normalized x-offset. Figure 4 shows a sample dialog box from NuMAD that displays the geometric parameters as well as a visualization for part of the blade. These geometric parameters significant for the automated reconstruction of the wind blade geometry. Each airfoil profile is divided into a series of segments that describe both the material properties of the composite surface and the points for the polyline that creates the internal structural spars.

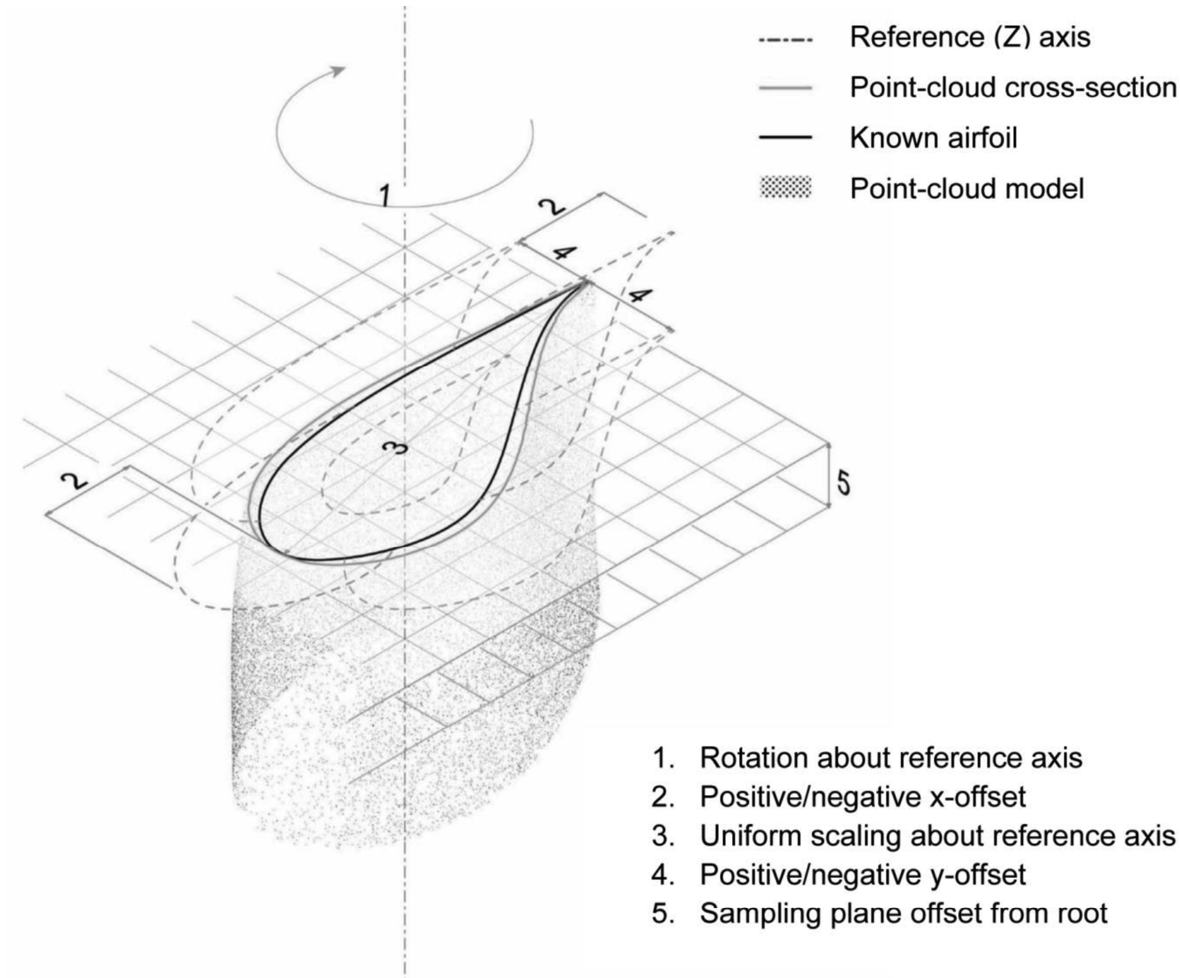


**Figure 5. Transformations used to position the airfoil on the point-cloud cross section.**

**Evolutionary Solvers:** The development of evolutionary solvers in computing is well documented and has been summarized by Eiben (2015). Evolutionary solvers work with populations of individuals that can recombine their characteristics—or genomes—to produce a population with greater fitness in a manner analogous to biological evolution. The fitness of the population is directed by maximizing or minimizing a single quantity. Evolutionary solvers always return a solution, and through time the solution improves eventually approaching a maximum or minimum in a given fitness landscape. Applied to the reconstructive modeling of wind blades, the individuals are known airfoils whose genomes are the geometric properties such as their rotation, translation, x-and-y offset from reference axis and chordal length along the reference axis. Figure 5 summarizes the transformations used to position a known airfoil within across-section of the point-cloud model.

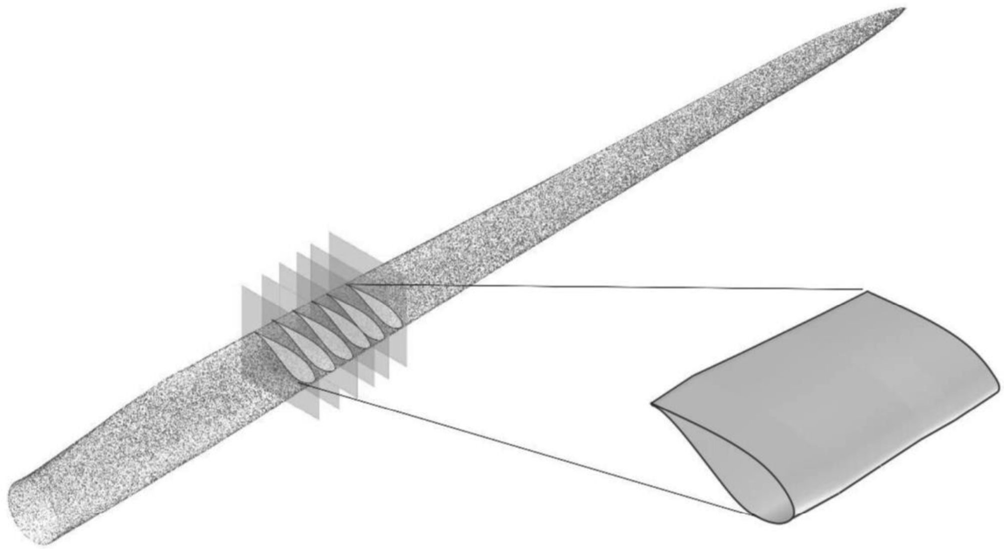

**Figure 6. Partial surface output from the routine.**

**Proposed Reconstruction Routine:** The proposed reconstruction routine developed by the authors consists of best-fitting a known airfoil profile against a section of the wind blade point-cloud model in a given sampling plane (specified as a Z offset from the root of the blade). Initial studies to create point-cloud models from physical artifacts utilized a small quad-bladed wood propeller, and the surface-reconstruction routine proved possible. For the purposes of this paper, a point-cloud model of Sandia National Laboratory 100 m prototype blade (SNL-100) was digitally created so that airfoil profiles selected by the routine could be compared to the actual profiles of the blade (Griffith and Ashwill 2011). Different resolutions of point-clouds were tested ranging from 10,000 to 1 million points, and ultimately a point-cloud of 500,000 points was chosen because of its ability to return errors of less than 100 mm while completing several thousand iterations.

The airfoil selection process is automated by linking to the routine a database of publicly available airfoil profiles, created as part of this project. This database contains a selection of normalized coordinates that describe airfoil profiles created by the National Advisory Committee for Aeronautics (UIUC 2018), Delft University (Berg 2012; UIUC 2018; Bertagnolio 2001), Aeronautical Research Institute of Sweden (Bjork 1990), and Risø-DTU National Laboratories (Bertagnolio 2001). Each airfoil shape is stored in the database as a set of XY points, with between 50 and 200 points for each airfoil.

During the runtime of the evolutionary solver, an airfoil profile is selected from the database and is compared to a point-cloud section in a 2D XY plane. Given the density of the 3D point cloud (500,000 points), the solver generally identifies between 500 and 700 points with essentially equivalent Z coordinates. Both the airfoil and point-cloud section curves are sampled at 100 points equidistant from each other. The fitness value is chosen as the mean distance between corresponding points on the airfoil and point-cloud section, and it is minimized by altering geometric characteristics such as the specific airfoil type, the distance from the root, chord length, rotation of airfoil in plane, and offset from reference axis. The routine goes through thousands of iterations where the fitness of each iteration progressively increases. This routine is repeated along key points of the blade such as the transitional region, plane of maximum chord, and mid-span. Once the cross-sections are established, a surface is created between these airfoils.

A test-case was used to re-create the blade surface of the SNL-100 blade from the point cloud between Z coordinates of 29 m to 39 m (Figure 6). The routine was run in 6 instances to fit 6 airfoils. In each instance, pairs of points sampled on the airfoil and point-cloud section were between 10 mm to 75 mm away from each other. When comparing the surface to the 3D point cloud, a mean distance of 10 mm is between a given 3D point in the point cloud and point on the recreated surface following the shortest normal vector.

## GENERATING THE INTERAL STRUCTURE OF THE BLADE

Once the external geometry of the wind blade is established, the process advances to generate the internal structure of the blade. The typical materials and relative thicknesses of the composite structures within the blade have been described in earlier work by the authors (Gentry et al. 2018). The aerodynamic forces generated on the blade are complex, but the lift component on the blade generates the flapwise bending moments that drive the design of the root section and spar cap (Schubel and Crossley 2012). Given the external geometry, and knowledge of the relative width of the spar cap, derived parametrically from the width of the blade at maximum chord, the algorithm calculates the effective flapwise moment of inertia at multiple stations along the reference axis. Given prior knowledge regarding the composite material strength and modulus and the calculated cantilever bending moment at the section, the thickness of the primary materials at that location can be established. The secondary structure (blade shell) is a composite sandwich panel, this structure can be selected based on a rule set with blade length and maximum chord dimensions as the input variables.

## CONCLUSIONS AND FUTURE WORK

This paper presents an automated routine that reconstructs a polysurface model from point-cloud representations of wind blades. To demonstrate the reconstruction routine, a digitally-created point-cloud model of the SNL-100-01 prototype blade was used. In the future, the routine will be tested with field-produced point-cloud models of wind blades so that the results can be more quantitatively compared and analyzed. Wind blades with reference axes other than a line pose a challenge because of the complexities in interpolating a smooth non-linear curve. In addition, the internal structure of wind blades will be refined after better understanding of their geometric relationships to the exterior surface geometry.

## ACKNOWLEDGEMENTS

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