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Constraint-based Shape Parameterization for Aerodynamic Design

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Abstract: We present a method for constructing design-appropriate shape parameterizations of discrete surfaces for optimization of flight vehicles. The method allows the designer to choose a set of points located on the aerodynamic surface to serve as design variables. Arbitrary geometric constraints can be prescribed and are intrinsically incorporated into the parameterization. The technique supports both fine-scale control and more rigid, large-scale deformation modes, enabling the recovery of standard wing design parameters. We show that local shape features, such as airfoil sections, can be preserved even under large-scale deformation. Deformations of high-resolution surfaces typically require seconds to compute. Parameterizations can be modified and refined at design time, allowing for incorporation of new design variables and constraints throughout the design process. We demonstrate the technique on demanding 3D aerospace geometry manipulation problems, including the creation of a parametric wingtip generator. We conclude with an airfoil optimization problem conducted in two stages, where the shape parameterization is enhanced between stages. This work is an important step towards our broader goal of offering aerospace designers more relevant, customized control over shape deformation.

Keywords: Aerodynamic shape design, optimization, discrete geometry, deformation, parameterization, constraints, constructive modeling, parametrization

1 Introduction

The ability to drive a baseline aerodynamic shape to one with superior performance hinges on the quality of the shape parameterization. Every set of design parameters inherently restricts the range of reachable shapes, which can be helpful or hurtful. On the one hand it is often useful to delimit the design space, both to simplify the optimization problem and to avoid exploring regions known to be off-limits, often for non-aerodynamic reasons. On the other hand, pre-set deformation mechanisms can restrict the design space in irrelevant ways, needlessly hindering the discovery of valid designs. Deliberate, informed tailoring of the design space to individual problems is crucial for effective design.

In constructive modeling approaches to design (e.g. CAD or custom in-house modelers), such customization is difficult. While shape parameters in constructive modelers are usually physically motivated, they are not always particularly relevant for aerodynamic design. It is often desirable to re-parameterize the shape before or during optimization, but this process is generally time-consuming and costly.

An alternate approach is to work directly with discrete geometry (e.g. triangulations or other surface meshes). With discrete geometry, there is no fixed set of shape parameters. The shape is free from the constraints of a particular constructive modeler. The discrete geometry approach thus has the potential to support custom shape parameterizations that are appropriate for the design problem at hand. Aerospace industry research on discrete geometry methods has resulted in several high-quality techniques for shape *deformation*. However, these techniques have had limited success in providing intuitive parameters for shape *design*, as they typically require time-consuming manipulation and grouping of large numbers of control points with little relevance to design.

In this work we present a technique for creating custom, design-appropriate shape parameterizations of discrete surfaces. Our approach is to leverage the smooth deformation techniques listed above, but to automate them and remove them from the designer's direct control. Instead, the designer directly selects and manipulates any number of points on the surface and prescribes geometric constraints, while an automated system solves for a smooth deformation of the remainder of the surface that satisfies the constraints. The method, called "constraint-based deformation", is in fact already widely used in the computer graphics (CG) community, and was only recently introduced into the aerospace community. Constraint-based deformation gives the designer direct control over the things that matter (i.e. the surface itself and geometric constraints), while eliminating the need to orchestrate the clouds of control points involved in discrete surface deformation. By supporting the construction of relevant design parameters and by exactly enforcing user-specified constraints, this technique can greatly improve the expression of design intent.

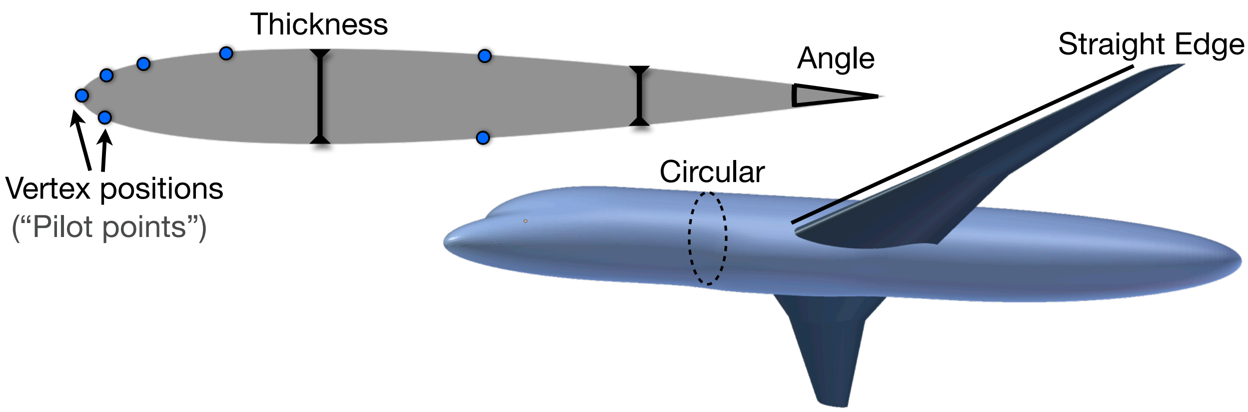

Figure 1: Some basic constraints in aircraft design.

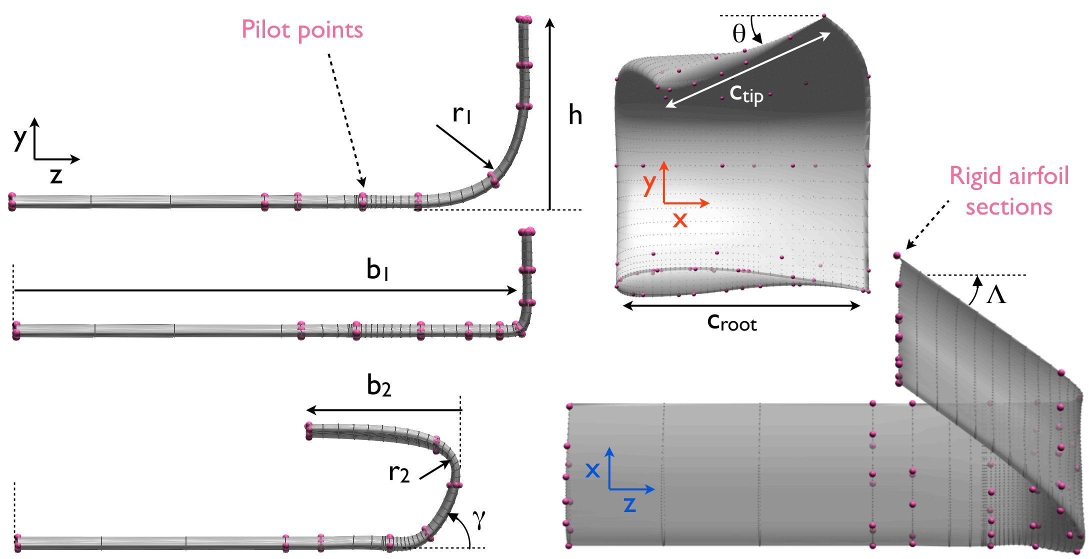

Figure 2: Parametric wingtip definition, showing various wingtips and some key parameters.