Comprehensive aircraft configuration designer for integrated product and process development

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Abstract

This paper describes an efficient aircraft geometry design tool which is necessary for design and analysis applications through Integrated Product and Process Development (IPPD). The design process decomposes aircraft geometry into several components to represent it precisely and realistically with a reduced number of shape control parameters. For this purpose, several configuration representation algorithms are thoroughly investigated and discussed. The proposed configuration generation algorithm employs the super ellipse equation with polynomial distribution functions, Class function/Shape function Transformation (CST) and can represent and manipulate complex shapes accurately with a small number of control parameters. A model of aircraft geometry, represented in this approach, can be applied to any stage of aircraft design and development with realistic and accurate configuration data. A solution for connecting and storing the represented shapes in a Product Data Management system is also developed and demonstrated. The proposed configuration design tool could be especially efficient when automation, flexibility and rapid changes of geometry are required in a short time and with low computational resources.

Keywords: Aircraft design; Wireframe; Parameterization; Aerodynamic surface representation; IPPD

Notations

API – Application Programming Interface
BOM – Bill of Materials
CAD – Computer Aided Design
CAE – Computer Aided Engineering
CAGD – Computer Aided Geometry Design
CFD – Computational Fluid Dynamics
CST – Class function/Shape function Transformation
DB – Database
DMU – Digital Mock-Up
EDF – Elliptical and Distribution Functions
FEA – Finite Element Analysis
GUI – Graphical User Interface
IPPD – Integrated Product and Process Development
MDO – Multidisciplinary Design Optimization
PDM – Product Data Management
UAV – Unmanned Aerial Vehicle

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1. Introduction

Geometry definition plays a key role in aircraft design, development and optimization. For efficient geometry generation, especially during the early stage of design, a step before the application of automated geometry generation is needed, i.e. a toolbox that will produce generic and parameterized aerodynamic surfaces, which takes into account special requirements and constraints. Among well-known general CAD packages, very few are specialized to aircraft design. General CAD systems offer solutions for providing data for general engineering systems and thus cannot entirely fulfil all configuration requirements of aircraft development throughout all design phases.

Several authors, including Trapp, Sobieczky [1, 2], Kulfan [3–5], Samareh [6] and Athanasopoulos [7], have studied and developed representation techniques and methods to overcome the aforementioned issues with aircraft shape representation. Among configuration design tools for aircraft, Generic Parameterized Aircraft Surface (Ge.P.A.S.) [8], RAGE [9] and RDS-Professional [10] are specialized to fixed wing aircraft design, and HESCAD [11] is specialized to the pre-conceptual design stage of rotorcraft. There are many parametric geometry creation and manipulation tools with GUIs [12–16]. These tools can provide considerable cost savings in the product design process through reduction of design time. For example, Vehicle Sketch Pad (VSP) [17] parametric geometry modelling tool developed by NASA is getting popularity in conceptual design of aircraft. Recently, in most CAD systems, special tools for customization or Application Programming Interface (API) connection are being improved, such as CAA, CATIA VBA, UGS NX Open API, etc. It is clear that the implementation of these new features in representation algorithms will give better functionality in terms of integration ability and suitability for MDO and IPPD.

In recent years, engineering systems, including automobile, ship and aircraft are being considered concurrently with different disciplines and objectives applied to the analysis of effects at the early stage of design. This is known as Integrated Product and Process Development (IPPD). However, analysis modules and disciplines are still not connected smoothly to the geometry module. Price et al. [18, 19] have investigated current developments and status of the integrated design approach.

Kulfan [3, 5] defines the desirable features of promising aerodynamic geometric representation techniques as: (a) mathematical efficiency (i.e. smoothness along axis, accuracy, numerical stability and robustness); (b) consistency and intuitiveness; (c) representation ability with a few variables and easy control capability (i.e. flexibility). However, to meet all these requirements in geometry representation is not an easy task. The main issue is how to define an acceptable (smooth, continuous, flexible, intuitive, robust, low-cost, etc.) geometry representation method while satisfying all these requirements.
This paper presents an automated configuration design method and tool for the more realistic representation of various aerospace vehicle geometries using fewer control parameters. The design tool builds an aircraft geometry using typical and common components and intended for using them in conceptual and preliminary design phases.

The proposed design and representation tool is based on an effective use of a super elliptic formulation with exponential and polynomial distribution functions in an example of configuration design. It is demonstrated that with this design method, designers can represent the geometry more realistically, quickly and efficiently, then can store the geometry data in a Product Database Management (PDM) system, and manipulate complex shapes with a small number of control parameters. An aircraft geometry model in an associative environment, which is represented more realistically and precisely, is applicable to different stages of the design and development lifecycle. This proposed tool could be especially efficient when automation, flexibility, rapid changes and shorter development time of geometry are required with small computational resources.

The remaining sections in this paper are organized as follows. In Section 2, the main flow and algorithm of Parameter-based Comprehensive Aircraft Designer (PCAD) which combines GUI, aircraft scheme selection, surface representation using elliptical and distribution functions (EDF) and DB tools are introduced. Section 3 introduces an associative-relational design example which is implemented using CAD software and the PDM process for aircraft design in an IPPD environment. Section 4 presents practical applications of CAD customization – a Geometry Representation System (GRS) for aircraft design and optimization. Finally, a conclusion is given in section 5.

2. Parameter-based Comprehensive Aircraft Designer (PCAD)

Compared to conventional design, parametric-associative design requires greater involvement of CAE models in the early stages of the project such as the feasibility phase and the concept

![Figure 1 Design expenditures in an aircraft design project [12]](image-url)
phase. This will lower the overall design costs and development risks. It will also result in a more balanced cost profile during the aircraft design process [20].

An industry-oriented approach of associative design with implementation of structural analysis was introduced in Ledermann’s works [12, 13]. A complex CAD design like a complete aircraft cannot be designed as one part. A huge amount of data, components and parts have to be organized in an intelligent way. Basically these designs can be split into parts and assemblies where assemblies are built up of several parts. An associative model allows different geometric objects to be interrelated [12].

PCAD for the IPPD presented in this paper is developed by meeting requirements such as visualizing the object during the design, making necessary decisions in step-by-step fashion and planning. In addition, the CAD-based design implemented in this way allows a surface model to be used in other analysis modules, such as “Aerodynamics”, “Structural”, “CFD”, etc. The relational-associative design concept offers the possibility of using an external surface model for the design of internal components. Representation of the model with a reduced number of control parameters gives convenient performance in optimization problems. The realistic behaviour of the surface allows the model to be used to control the manufacturing process. A CAD system Digital mock-up (DMU) tool can predict clashes, gaps, various errors and ambiguous units in the assembling process. A PDM system easily handles the manipulation and automation of the whole process and manages safely all output information. The open architecture used makes the package available for connection to other applications and solutions to this system.

2.1. PCAD architecture

The PCAD conceptual architecture is introduced in Fig 2. This tool consists of a GUI (Graphical User Interface), an aircraft “configuration scheme selection” decision-making tool, “surface coordinate points generator” (“control points grid”), customized CAD software adapted to the needs of designers and a commercial PDM tool.
2.2. Configuration representation algorithm

There are several crucial issues affecting the representation aircraft geometry in terms of purpose and fidelity during design stages. Basically, main components and units of an aircraft can be considered as free-form surfaces.

Main components of the types of aircraft that are most commonly exploited are shown in Fig.3: fixed wing airplane, helicopter and missile.

In terms of the main components, the geometry and types of most common aircraft have many similarities such as fuselages, stabilizers, wings, etc. The methods of representing such parts can also be considered to be similar. According to references [3-5, 8] aircraft components are divided into two main types: wing type geometries and fuselages or fusiform type shapes.
Aircraft shapes creation procedure is introduced below, which is based on using polynomial functions and curves for surface generation. The flowchart of this process is shown in figure 4. In the early design stage of development, a designer can adjust all necessary key geometry parameters manually to generate a surface. Firstly, from the GUI, the designer inputs all necessary information (function coefficients, parameters, etc.) according to properly defined boundaries to represent the split units: cross-sectional and longitudinal shapes. Then, the program calculates the output points as logically sectioned geometric parts. Consequently, the CAD software generates a surface using that output points. According to this approach, all manipulations and adjustments are performed by the designer.
In the preliminary stage of design, various analysis tools are used and the representation geometry must coincide with the initial object. Extra precision gives better results in terms of validity and robustness. Hence it reduces the preliminary design time and cost. Fig. 4 shows the fitting process for the existing shape from discrete data points to obtain the function coefficients. The obtained coefficients are used in shape generation with many points using approximation functions. The entire geometry is formed by cross-sectional and longitudinal shapes. The surface generated by CAD is stored in a PDM database. A more detailed explanation on how to generate curves, surfaces and the PDM data structure is given in the following sections.

2.2.1. CST

The CST method is based on analytical expressions to represent and modify the various shapes [3-5]. The components of this function are the “shape function” and “class function”. The shape function provides direct control over the key parameters of the geometry. The class function modifies the geometry according to class types, such as airfoil type shape, ellipse, cone type shape, etc. The curve ordinates are defined in CST by the following equation:
\[ y(x/c) = C_{N1}^{N2}(x/c) \cdot S(x/c) \]  

where \( C_{N1}^{N2}(x/c) = (x/c)^{N1}(1-x/c)^{N2} \) : class function,

\[ S(x/c) = \sum_{i=0}^{n} [A_i \cdot (x/c)^i] \] : shape function,

\( A_i \): shape function coefficients

\( N1, N2 \): exponents

\( x \): non-dimensional values from 0 to 1.

\( c \): chord length

To formulate the CST method, Bernstein polynomials are used as the shape function:

\[ S_i(x) = K_{ii} x^i (1-x)^{n-i} \]  

where \( K = \binom{n}{i} = \frac{n!}{i!(n-i)!} \) : binomial coefficients

\( n \): order of Bernstein polynomial

\( i \): numbers 0 to \( n \)

The efficiency of the airfoil representation by CST is compared with NURBS and shown in Fig. 5-a. In this example, for the NURBS generation, new points are used in a 4th order Cox de Boor algorithm and 65 points are generated for representation of each (upper and lower) curve [21]. In this case, the control variables are the ordinates of the control points (5 variables for the upper curve and 5 for the lower curve ordinates). The CST method with 4 control variables has a better fit to the existing airfoil than NURBS, which uses 10 control variables for fitting.

Figure 5 Transonic RAE 2822 airfoil representation: (a) CST and NURBS; (b) absolute error comparison

Fig. 5-b shows the absolute errors in airfoil generation with CST and NURBS. It is required at least 10 control points to generate the airfoil using NURBS. Generation by NURBS of the aft part of airfoil has larger errors.
Fig 6 shows a representation of a helicopter rotor blade with three different airfoils (cross-sections), chord lengths, twisting, leading edge (LE) angle, and $L_1$, $L_2$, $L_3$ offsets (Fig. 6)

2.2.2. Super ellipse equation

The general Cartesian notation of the form comes from the French mathematician Gabriel Lamé who generalized the equation of the ellipse:

$$|x/a|^n + |y/b|^m = 1, \ (n,m > 0)$$

(3)

The solution of function $y$ becomes (Fig. 7-a):

$$|y| = b \cdot \left(1 - |x/a|^n\right)^{-\frac{1}{m}}, \ (n,m > 0)$$

(4)

Figure 6 Rotorcraft rotor blade surface representation using CST

Figure 7 Super ellipse functions: (a) Non-dimensional functions (b) Dimensional scaled and positioned functions
2.2.3. Aircraft geometry representation using elliptic and distribution functions (EDF)

To capture the whole design space and to easily control the function in it, we will use Eq. (4) in non-dimensional form, thus the $a$ and $b$ values should always be equal to 1. The value $x$ should be in the interval [0, 1]. For convenience, all non-dimensional notations could be identified like:

$$|\mathbf{y}| = (1 - |\mathbf{y}|)^{\frac{1}{2}} (n, m > 0) \quad (5)$$

Fig. 7-a shows super ellipse function with various values of $n$ and $m$ in non-dimensional space.

To represent bodies like an aircraft fuselage and manipulate them efficiently, it is necessary to use a width, height and reference distance. Thus, we apply Eq. (5) to the upper and lower parts of the fuselage body shape (Fig. 7-b).

Dimensional $y$-coordinates in a Cartesian system are defined as:

$$y_{upper} = \bar{x}_1 \frac{W}{2}$$
$$y_{lower} = \bar{x}_2 \frac{W}{2} \quad (6)$$

where: $W$ is the width, $\bar{x}_1$ is a non-dimensional value between [0,1] and $\bar{x}_2$ is a non-dimensional value with the opposite decrement [1,0].

Dimensional $z$-coordinates in a Cartesian system are defined as:

$$z_{upper} = \bar{y}_1 \frac{H}{2} + z^*$$
$$z_{lower} = \bar{y}_2 \frac{H}{2} + z^* \quad (7)$$

where: $\bar{y}_1 = f(\bar{x}_1)$ and $\bar{y}_2 = f(\bar{x}_2)$ are non-dimensional functions of $\bar{x}_1$ and $\bar{x}_2$ respectively; $H$ is height; $z^*$ is a reference value.

Rotorcraft fuselage geometry has a more complex behaviour in the longitudinal direction. In terms of manipulation of shapes, it is important to divide it into more divisions. Airplane fuselage or missile body geometry is simpler than helicopter fuselage, hence it requires fewer sections in the longitudinal direction.

Helicopter fuselage geometry is divided into 5 sections as shown in Fig. 8. Each section has different distribution functions which correspondingly represent the following parameters: width/2, height, reference curve, $m$ and $n$ values for each upper and lower part. Marginal $W/2$, $H$ and $z^*$ single values (Eq. 6,7) from each section are defined as scaling parameters.
Table 1 Distribution functions and summary of design variables* by fuselage sections

<table>
<thead>
<tr>
<th></th>
<th>Nose</th>
<th>F1</th>
<th>F2</th>
<th>F3</th>
<th>Tail</th>
<th>Number of Control Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference Curve</td>
<td>$f_i(x) = a^*\exp(b^*x)$</td>
<td>$f(x) = p_1^*x^2 + p_2^*x + p_3$</td>
<td>$f(x) = a^*\exp(b^*x)$</td>
<td>$f(x) = a^*\exp(b^*x)$</td>
<td>$f(x) = a^*\exp(b^*x)\text{ (5)}$</td>
<td>5 (5)**</td>
</tr>
<tr>
<td>Height</td>
<td>$f_i(x) = a^*\exp(b^*x^{1/c})$</td>
<td>$f(x) = p_1^*x^2 + p_2^*x + p_3$</td>
<td>$f(x) = a^*\exp(b^*x)$</td>
<td>$f(x) = a^*\exp(b^*x)$</td>
<td>$f(x) = a^*\exp(b^*x)\text{ (5)}$</td>
<td>5 (5)</td>
</tr>
<tr>
<td>Width/2</td>
<td>$f_i(x) = a^*\exp(b^*x^{1/c})$</td>
<td>$f(x) = p_1^*x^2 + p_2^*x + p_3$</td>
<td>$f(x) = a^*\exp(b^*x)$</td>
<td>$f(x) = p_1^*x^2 + p_2^*x + p_3 + p_4$</td>
<td>$f(x) = a^*\exp(b^*x^{1/c})\text{ (5)}$</td>
<td>5 (5)</td>
</tr>
<tr>
<td>Shape control value m</td>
<td>$f_i(x) = a^*x^m + c$</td>
<td>$f(x) = -x^m + b$</td>
<td>$f(x) = a^*\exp(b^*x)$</td>
<td>$f(x) = -x^m + b\text{ (1-x)^m + b}$</td>
<td>$f(x) = a^*\exp(b^*x^{1/c})\text{ (5)}$</td>
<td>5</td>
</tr>
<tr>
<td>Shape control value n</td>
<td>$f_i(x) = a^*x^n + c$</td>
<td>$f(x) = -x^n + b$</td>
<td>$f(x) = a^*\exp(b^*x)$</td>
<td>$f(x) = -x^n + b\text{ (1-x)^n + b}$</td>
<td>$f(x) = -x^n + b\text{ (1-x)^n + b}$</td>
<td>5</td>
</tr>
<tr>
<td>TOTAL</td>
<td>25 (15)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Most sensitive single variable was selected from each function.
**Number of scaling parameters

Table 1 shows an example of helicopter fuselage distribution functions according to sections and possible control variables. $a$, $b$ and $p_1$, ..., $p_4$ values are empirical values. Dimensional values are obtained by multiplying the corresponding non-dimensional values by scaling parameters (i.e. number of scaling parameters shown in Table 1 in brackets). Dimensional $x$
values obtained by multiplying dimensionless $x$ values from each section to corresponding $L_1$, $L_2$, $L_3$, $L_4$ and $L_5$ distances.

### 3. Associative and collaborative design

In this section, some application and solutions for collaborative design, and some methods for how to use this approach in IPPD framework are given.

An example of the design and assembling of a helicopter blade’s components using “published” tools is given in Section 3.1. Section 3.2 introduces a PDM system application into a framework with many modules which can be one solution for collaborative design and data management.

#### 3.1. Publications on CAD systems

Generated airfoil cross-sections and spanwise stations are connected by parametric relations. Fig. 9 shows a flow sequence of associative modelling method for blade surface generation and new component creation using published information. The publication contains all necessary information about the parent element: part name, number, and sub-element from which the publication is generated.

![Figure 9 Main rotor blade surface creation and its relations with solid, inner components](image)

Fig. 9 Publication (sharing and linking) of key elements

Main rotor blade inner components are designed in the same way as illustrated in Fig. 9 and assembled together. Fig. 10 shows the main structure components of a composite rotor blade: web, D-spar, cap, skin and honeycomb filament.
3.2. Collaboration with PDM

Product Data Management (PDM) deals with all related information about a product. This information could be design geometry, engineering drawings, project and process plans, CAD part files, assemblies, product specifications, numerical-control machine tool programs, analysis results, bills of material (BOM), etc.

Figure 10 Main rotor assembly process

Figure 11 PDM process for aircraft design in IPPD environment
Fig. 11 shows a rotorcraft blade design process application from concept creation up to storing of information in a DB. In our design application, first key geometrical parameters are defined, and then the outer surface model is generated using these parameters. Solid components are created by reference to the outer surface geometry and all components are assembled and saved in the PDM database, then prepared to further using them in other modules (i.e. disciplines: manufacturing planning and process simulation, CFD, structural analysis, etc.). Collaborative work between engineers or participants of the program can also be undertaken within PDM. User A, user B, etc. can join a project, work in it or manage it with a unique ID.

4. Helicopter configuration design using PCAD

PCAD includes airplane, helicopter, missile and fighter geometry generator tools. The main GUI (Fig. 12) was designed in Microsoft Visual Basic and the input interface and programs for the customization part were developed using CATIA VBA [22] (Fig. 15-17).

The implementation of processes explained in Section 2.2 is done with MS Excel. CST and EDF methods were used for the calculation of necessary coordinates. The transfer of point
coordinates into an Interactive Shape Generator allows the geometry to be built faster than with other approaches. Two approaches with connection to MS Excel are available. The user can choose one of several options (radio button options) available in the representation tools selection form as shown in Fig. 13.

The first option deals with designer decisions (fig. 14). Using the second option, the user can input 300 control points (10 cross-sections, 4 longitudinal guides) for geometry generation (fig. 15). The third option calls the Interactive Shape Generator directly (Fig. 16).

The interactive shape generator creates geometry parts, such as fuselage shapes, rotor blades, bumps, vertical and horizontal tails, landing gear, etc. separately in a step-by-step fashion. Completed parts can be saved and assembled.

Fig. 17 shows the fuselage generation input form. This form allows to create and update the longitudinal stations (Fig. 18-a); crown and contour lines (Fig. 18-b); cross-sections (Fig. 18-c) and input all necessary information to define a fuselage geometry.
Airfoil profiled shapes such as wing, blade and empennage elements were created using the CST method (section 2.1.1). The input forms for helicopter rotor blade and hub elements are shown in Fig. 19.
The Interactive Shape Generator’s assembly creation form is shown in Fig. 20. Here, the user can assemble parts and units which were created before. Additionally, it is possible to add other parts or assemblies into the designed model.

Fig. 21-22 shows some examples of representations of existing aircraft fuselage geometries (UH-60 helicopter and CRJ200 commercial airplane) generated using the EDF method. EDF method allows generating a fuselage like shapes which is shown in Fig. 21 using 25-30 control variables. The representation of conventional aircraft configurations needs less control variables.
than helicopters. The conventional passenger aircraft geometry which is shown in Fig. 22 is generated with 20-25 control parameters.

Figure 23 Representation of whole configuration geometry
Fig. 23 shows steps of rotorcraft geometry design and configuration assembly. As shown in this figure, the shapes are very smooth, well distributed and realistic.

The main advantage of PCAD is availability of step-by-step geometry creation and modifying feature. A designer can make necessary decisions – modify and arrange the curves which later can be used to generate aircraft surface and whole configuration. PCAD does not require special CAD skills from the user, thus any user can build the necessary configuration in a very short time. Additional efficiency of PCAD is its open environment. It works under CATIA V5 CAD system [22]. The generated CAD data can serve in various other analysis programs or work together with other CAD software.

5. Conclusions

An interactive and generic aircraft geometry representation tool – Parameter-based Comprehensive Aircraft Designer (PCAD) for an IPPD framework was presented and some implementations were demonstrated.

Geometry representation methods – Class Function/Shape Function Transformations (CST) and Elliptic Distribution Function (EDF) method – were introduced. The EDF method was proposed to represent generic fuselage shapes.

PCAD allows the designer to create aircraft geometries in a step-by-step fashion and to manipulate them in real time. This tool also can be used to describe the relations between the performance and analysis modules in IPPD and MDO applications, which can deal with an aircraft’s weight, size, volume and performance.

An associative design application and PDM structure is presented as an example of helicopter blade assembly. The associative assembly approach gives good accuracy and a logical way to design and develop aircraft units.

The tools and approaches shown in this paper could be part of an aerospace-related CAD package or could be offered as a visualization tool for various frameworks, grid generation or analysis software. In addition, all the tools described above allow the design time and cost to be reduced, which is very important in aeronautics and aerospace development.

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