Knowledge Based Integrated Multidisciplinary Aircraft Conceptual Design

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Cover:

"Johnson's Theorem: If three congruent circles all intersect in a single point, then the other three points of intersection will lie on another circle of the same radius. This simple little theorem was discovered by Roger Johnson(1890-1954) in 1916. The anti-complementary circle is tangent to the three Johnson circles and the radius is twice that of the Johnson circles."

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To Krishnaveni

Arise! Awake! and Stop not until the
Goal is reached.

- Swami Vivekananda

Abstract

With the ever growing complexity of aircrafts, new tools and eventually methods to use these tools are needed in aircraft conceptual design. To reduce the development cost, an enhancement in the conceptual design is needed.

This thesis presents a knowledge-based aircraft geometry design tool RAPID and the methodology applied in realizing the design. The parameters used to create a geometry need to be exchange between different tools. This is achieved by using a centralized database or one-data concept. One-database will enable creating a less number of cross connections between different tools to exchange data with one another. Different types of aircraft configurations can be obtained with less effort. As RAPID is developed based on relational design, any changes made to the geometric model will update automatically. The geometry model is carefully defined to carry over to the preliminary design.

The validation of RAPID is done by implementing it in different aircraft design courses at Linköping University. In the aircraft project course, RAPID was effectively used and new features were added to the obtained desired design. Knowledge-base is used to realize the design performance for the geometry with an integrated database approach for a multidisciplinary aircraft conceptual design.

Keywords: Knowledge-base, Aircraft, Conceptual Design, CAD, XML Database, Multidisciplinary, Optimization

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Abbreviations

<i>ADS</i>	Aircraft Design Software
<i>AR</i>	Aspect Ratio
<i>BeX</i>	Berry Excel
<i>CAD</i>	Computer Aided Design
<i>CATIA</i>	Computer Aided Three-dimensional Interactive Application
<i>CDT</i>	Conceptual Design Tool
<i>CEASIOM</i>	Computerized Environment for Aircraft Synthesis and Integrated Optimisation Methods
<i>CFD</i>	Computational Fluid Dynamics
<i>DOM</i>	Document Object Model
<i>EKL</i>	Engineering Knowledge Language
<i>FAR</i>	Federal Acquisition Regulation
<i>KBS</i>	Knowledge Based System
<i>KBE</i>	Knowledge Based Engineering
<i>KP</i>	Knowledge Pattern
<i>PADLab</i>	Preliminary Aircraft Design Lab
<i>PC</i>	Power Copy
<i>RAPID</i>	Robust Aircraft Parametric Interactive Design
<i>RAGE</i>	Rapid Aerospace Geometry Engine
<i>RDS</i>	Aircraft Design Software package
<i>SFC</i>	Specific Fuel Consumption
<i>TR</i>	Taper Ratio
<i>UDF</i>	User Defined Feature
<i>VB</i>	Visual Basic
<i>VBA</i>	Visual Basic for Applications
<i>VSP</i>	Vehicle Sketch Pad
<i>XML</i>	Extensible Markup Language
<i>XLST</i>	Extensible Stylesheet Language

Nomenclature

The terminology used in this thesis are as shown in the table.

Quantity	Description
A_R	Aspect ratio
C_S	Fuselage cross-section
C_S^i	i^{th} cross-section
C_u	Upper curve
C_l	Lower curve
C_c	Combine curve
$f_i(Z)$	Piecewise polynomial functions
f_u	Fuselage function
H_f	Height of fuselage
k	Kink Position
L_f	Length of fuselage
n_p	Number of parameters
P_i	Points on a spline
$p_{1,2,...n}$	Control points of cross-section
S	Reference wing area
S_p	Splines
w	Wing function
w_p	Wing partitions
w_p^i	i^{th} wing partition
W_f	Width of fuselage
Γ	Dihedral
θ	Incidence/Twist
λ	Taper ratio
Λ	Sweep
$\alpha_{p_{2,3,5,6d}}$	Angle measured w.r.t horizontal or vertical

Papers

The following Papers [I] [II] [III] [IV] are an integral part that forms this thesis and will be referred by Roman numerals. The papers are printed in their original-form with the exception of minor errata and adjustment of text and figures in-order to maintain same consistency throughout this thesis.

- [I] Raghu Chaitanya M.V., Tarkian M., and Jouannet C. “Model Based Aircraft Control System Design And Simulation”. In: *27th Congress of International Council of the Aeronautical Sciences*. 2010.
- [II] Safavi E., Raghu Chaitanya M.V., Ölvander J., and Krus P. “Multidisciplinary Optimization of Aircraft Vehicle System for Conceptual Analysis”. In: *Aerospace Sciences Meetings*. American Institute of Aeronautics and Astronautics, Jan. 2013. DOI: [10.2514/6.2013-282](https://doi.org/10.2514/6.2013-282).
- [III] Raghu Chaitanya M.V., Berry P., and Krus P. “RAPID - Robust Aircraft Parametric Interactive Design : (A Knowledge Based Aircraft Conceptual Design Tool)”. In: *4th CEAS: The International Conference of the European Aerospace Societies*. 2013, pp. 255–262.
- [IV] Raghu Chaitanya M.V., Staack I., and Krus P. “Integrated Aircraft Conceptual Design”. In: *4th CEAS: The International Conference of the European Aerospace Societies*. 2013, pp. 263–269.

Papers not included

Papers [V] and [VI] are not included in this thesis, however establish a good background for this thesis.

- [V] Staack I., Raghu Chaitanya M.V., Berry P., Melin T., Amadori K., Jouannet C., Lundström D., and Krus P. “Parametric Aircraft Conceptual Design Space”. In: *Proceedings of the 28th International Congress of the Aeronautical Sciences*. 2012.
- [VI] Singh A., Raghu Chaitanya M.V., Govindarajan V.K., and Krus P. “Knowledge Based Design Methodology for Generic Aircraft Windshield and Fairing-A Conceptual Approach”. In: *Aerospace Sciences Meetings*. American Institute of Aeronautics and Astronautics, Jan. 2013. DOI: [10.2514/6.2013-469](https://doi.org/10.2514/6.2013-469).

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1

Introduction

Conceptual design is the early stage of aircraft design process where results are needed fast, both analytically and visually so that the design can be analysed and eventually improved in the initial phases. Although there is no necessity for a Computer Aided Design (CAD) model from the very beginning of the design process, it can be an added advantage to have the model to get the impression and appearance.

1.1 Background

AIRCRAFT DESIGN is a complex process that involves different disciplines together to obtain a holistic approach. Modern aircraft have become more expensive and the time taken to build has increased considerably [1]. Figure 1.1 shows delay in different aircraft projects. An improvement in the conceptual design is needed to decrease the overall development time and cost for an aircraft. In conceptual design the results are needed faster both analytically and visually so that the design can be modified or changed at the earlier stages.

The three main design stages of an aircraft design process are Conceptual design, Preliminary design and Detail design. After the Detail design the aircraft is verified by experimenting with a prototype testing and finally full production [2] as shown in Figure 1.2. Different designs need to be analysed and verified in the conceptual design before going with the preliminary design. The design has to be approved before continuing with the preliminary design as it incurs an increase in the cost of the project.

Conceptual design tools have a constant need for refinement and im-

Figure 1.1 Time delay in Aircraft projects (adapted from Scminder [1]).

Figure 1.2 Aircraft development process (adapted from Brandt et. al.) [2]

provement. One such much needed enhancement is to be able to communicate between the analytical design tool and the 3D environment, i.e. CATIA[®] [3]. Data communication between conceptual design programs has always been a major obstacle which now has a possible solution through this work, presently being done at Linköping University. A seamless connection appeals to the designer but it has to work both ways. There are a handful of existing software tools in the industry, at

universities and research centres. Some have connections to CAD software but the connection is usually not seamless and even more rarely they work bi-directional [V]. Existing aircraft conceptual design tools are:

- RDS [4]
- VSP [5]
- CDT [6]
- J2 Universal Tool Kit [7]
- ADS [8]
- Piano [9]
- RAGE [10]
- CEASIOM [11]
- PADLab [12]

1.2 Aim

The objective of this thesis is to create a framework for aircraft conceptual design and a database to have a flexible and close integration of CAD and supplementary tools. The geometry that is created using knowledge-based engineering techniques is to be subsequently propagated to preliminary design. The framework also attempts to address one tool vis one database concept.

RQ1 : Is it possible to have a tool for geometry definition and visualization with a high degree of design automation where the aircraft models can be gradually developed and also propagated from conceptual to preliminary design?

RQ2: What kind of framework is needed to exchange the data develop from the model from RQ1?

RQ3: What is the level of fidelity needed for the geometric model and how to implement it in a commercial CAD environment?

RQ4: Is it possible to create a water tight model by using the knowledge-based techniques to propagate the geometry to CFD?

1.3 Delimitations

A brief overview of the knowledge-base and design automation is discussed, more focus is on the implementation of the same in this work. Explanations of different systems that were created in Hopsan and Dymola are not handled in this thesis. Tango design methodology and its implementation is not focused. An implementation of the XML integration process with RAPID and Tango is illustrated. Optimization frameworks that are used in this work hitherto are presented.

1.4 Contribution

This thesis proposes knowledge-based tool integration in aircraft conceptual design process. Knowledge-based geometry design tool RAPID is developed to help the designers realize the geometry of the aircraft at the earlier stages. The geometry created by using RAPID can be evolved to obtain a very high fidelity model/design. This facilitates for propagation of the geometry from conceptual design to preliminary design. The geometrical data can be stored in database and retrieved from the same. The thesis also explores different framework integrations in the conceptual aircraft design process.

"Scientists discover the world that exists; engineers create the world that never was." - Theodore von Karman

2

Design Methodology

This section describes the methodology followed to create RAPID as knowledge based aircraft conceptual design tool.

2.1 Knowledge-based Engineering and System

Knowledge Based Engineering (KBE) is reusable information that exists in the specific method or form; this knowledge is reused either manually or automatically and the whole process of using this existing knowledge such that it adapts to the new environment is termed as Knowledge Based System (KBS) [13] [14]. Verhagen et. al. [15] have presented many definitions of KBE/KBS from several authors and also showed examples of KBE project results. KBE is a technology initiated by Concentra Corporation [16] and is in existence for a couple of decades. More and more people have seen the need [17] and also developed an application in aircraft design based on KBE [18]. Nowadays, most of the CAD software is embedded with this technology as packages e.g. knowledgeware in CATIA, knowledge fusion in NX [19] and expert system in Creo [20] (formerly pro-e).

The KBE/KBS automation is performed in CATIA using the *Power Copy* (PC) and the *User Defined Feature* (UDF) wherever necessary. VB scripts use the power copies and KP uses UDF to save the knowledge that is created for automation. PC or UDF is a set of features stacked together that can be reused at a later stage. A catalog is needed to

store the location of the UDF. The KP algorithm script is written using the *Engineering Knowledge Language* (EKL) to control the UDF. UDF is used repeatedly to obtain a desired configuration. Further the UDF can be updated depending on the requirement and used accordingly. Creating the initial KBS is time consuming and the user needs to have some knowledge of the system in case of modifying it; however, once it is built there are numerous advantages of it and it could help the user build the necessary system faster and in less time. The Figure 2.1 [21] shows that by adopting KBE the time taken for the routine tasks can be minimized.

Figure 2.1 Design time by adopting KBE (adopted from Skarka) [21].

2.2 Level of fidelity

The frameworks similar to Paper [IV] and as shown in Figure 6.3 are CESIOM [22] by Royal Institute of Technology, design and engineering engine (DEE) by TU Delft [18] and DLR framework [23]. CESIOM also shows that the geometry created can be propagated to low and medium fidelity of CFD. All the above mentioned frameworks use the in-house tools developed by respective institutions/research organization. The main reason to use the commercial tools in this framework is to facilitate

direct implementation of the tool framework in the industry. This will reduce the time for the industry implementing the framework as it need not redo all that has been done during the conceptual design.

Figure 2.2 Model fidelity levels used in this framework (adapted and modified from Nickol) [24].

2.3 Effective parametrization

A good parameterization is to change the design according to designers' intentions. In a KBS, there is a requisite for effective parameterization to obtain a good working system. In this circumstance, there can be different layers of parameterization involved in the entire aircraft (Figure 2.3). In RAPID, there are several layers of relational design, thus making it a complex model. Global references are the first set of parameters to initialize the positions of different objects such as fuselage, wing, horizontal tail, vertical tail, canard, engine etc. The second set of parameters gives the initial layout/shape of the aircraft, e.g. fuselage length, height and width that gives effective dimensions to different objects and forms the bottom-up approach in RAPID.

- **Global references:** Main positions of all the objects such as fuselage, wing, horizontal tail, vertical tail, canard and engine.

Figure 2.3 *Design methodology applied in RAPID.*

- **Interrelated references:** These are the references needed to size the aircraft. For example, the vertical tail reference area is dependent on the fuselage and its position from the origin; the horizontal tail and canard reference area depends mainly on their respective positions from global origin and the wing area. An overall two-dimensional sketch is obtained after completion of this phase.
- **Relational references:** These are the references that help to give the shape / volume of the aircraft. For example, instantiation of number of fuselage frustums or number of wing partitions etc.
- **Sub relational references:** These the relational parameters that are available after instantiation of the instances of a number of frustums or number of wing parameters. There can be several layers of sub-relational references depending upon where the instances

follow.

2.3.1 Parametrization Example

To create “ n ” number of points with a reference from the given coordinate system, there is a necessity of “ $3n$ ” parameters even if all the points are to be of the same length in Z-direction. If all the four points used to create a rectangle as shown in Figure 2.4 are created with a reference from the given coordinate system then twelve parameters are needed. To reduce the number of parameters an efficient parametrization is necessary, i.e., relational parametrization. The above mentioned example is modified for the efficient parametrization by using only less than half of the parameters needed.

Figure 2.4 *Parametrization Example*

To effectively create a point P_1 from a given coordinate system three coordinates (x, y, z) are required. Point P_2 is created from point P_1 along the Y-axis with a distance (y_1) , by doing so reduces the number of variable parameters that need to be defined to one parameter. Points P_3 and P_4 are created from points P_2 and P_1 respectively, along the X-axis with a distance (x_2) . In total the number of parameters needed from the relational parametrization is only five. An extra two more parameters are needed to modify the shape of the rectangle to obtain any quadrilateral. In Chapter 5, a practical application of the parameterization is presented for better understanding of effective parameterization. From Table 5.3 it can be observed that the robustness of the kinked wing have increased approximately 30 % by effective parameterization. Kulfan [25] presents parametric geometrical method that can be applied to obtain wide range of geometry objects.

"To know what you know and what you do not know, that is true knowledge." - Confucius

3

RAPID - Robust Aircraft Parametric Interactive Design

RAPID (Figure 3.1) is a geometry oriented design tool used in the framework of aircraft conceptual design. The core incentive to use CATIA is to allow the geometry propagation from conceptual design to preliminary design. Knowledge Pattern (KP) and Visual Basic (VB) embedded in CATIA are used for automation at necessary stages. There are three ways the user can design the aircraft in RAPID.

- By modifying the existing model after loading from XML data library (Figure 3.3).
- By updating the model from the Sizing Excel (Figure 3.2).
- By bottom-up design approach (Figure 3.5).

The bottom-up design approach can be employed in RAPID to design from scratch or the user can load the existing aircraft model from the XML data library. The user begins by modifying the fuselage curves according to design requirements and later adapting the wing. The empennage is automatically sized depending on the given fuselage parameters and wing parameters. The adaptability of the model helps to obtain different aircraft configurations.(Figure 3.4)

Figure 3.1 RAPID Tool.

Figure 3.2 User interface for Geometry.

Figure 3.3 *Example of Civil transport aircraft geometry loaded from database.*

Figure 3.4 *Different aircraft configurations of geometry model RAPID.*

3.1 Geometry Model

After the initial setup of the wireframe model of the aircraft, a more detailed geometry can be developed (Figure 3.3). The user chooses the number of frustums needed for the fuselage and the number of partitions needed for wing, empennage and canard depending on the requirement.

3.1.1 Fuselage Geometry Description

The Fuselage wireframe is composed of four supporting splines; they are upper curve, bottom curve, side curve and center curve (Figure 3.5). The splines are created in desired manner which are then taken as reference for the instantiation of frustums. A frustum is formed by two Bezier curves joined by a surface. Bezier curves are parametric and can be modified to get desired cross-section at each frustum (Figure 3.6).

Figure 3.5 Fuselage curves in Sizing Excel (Top); Fuselage curves in RAPID (Bottom).

Establishing global fuselage geometry

$$fu = f(S_p, L_f, W_f, H_f, C_s) \quad (3.1)$$

$$| S_p(Z) = \sum_{n=0}^n f_i(z) P_j \quad (3.2)$$

$$\begin{aligned} j &= [2, n); P_0^x = 0; P_n^x = L_f \\ n_x - 1 &< n_x < n_x + 1 \\ \Delta x &= \frac{L_f}{n - 1} \\ n &\in \mathbb{N} \end{aligned}$$

A quarter of the fuselage cross-segment is portrayed by third-order Bezier curve. The angle is measured from the horizontal line for "upper line" and "lower line" and angle is measured from the vertical line for "side upper line" and "side lower line". The Points 1, 4 and 7 shown in Figure 3.6 are the intersection points with the fuselage curves while points 2, 3, 5 and 6 are positioned along the respective lines as a fraction.

Figure 3.6 Description of RAPID fuselage Crosssection [V]

Establishing fuselage cross-section

$$C_s^i := f(p, \alpha) \quad (3.3)$$

$$\begin{aligned}
 & | \ i = 1, 1, \dots n \\
 & n \in \mathbb{N} \\
 & [p_1^i, p_4^i, p_7^i] := f(C_u, C_l, C_c, C_s^i) \\
 & [p_2^i, p_3^i, p_5^i, p_6^i] \in [0, 1] \\
 & [\alpha_{p_2}^i, \alpha_{p_3}^i, \alpha_{p_5}^i, \alpha_{p_6}^i] \in \left[0, \frac{\pi}{2}\right]
 \end{aligned}$$

3.1.2 Wing Geometry Definition

Wing wireframe is generated by taking the reference area, taper ratio and aspect ratio as reference. The user has an option to choose the angle either from leading edge or 25% root chord to obtain trapezoidal wing area (shown in dotted line in Figure 3.7). There also exists another reference area method to choose from such as Double delta, Gross Method and Wimpres Method. The RAPID area method uses the trapezoid area as a reference, after instantiating required number of partitions the chord at each airfoil can be modified to obtain different wing shape as shown in Figure 3.7. The final wing area is obtained by the sum of all the instantiated partitions.

Figure 3.7 Different wing shapes modified after instantiation of partitions.

Establishing wing geometry

$$w = f(S, A_R, \lambda_i, \wedge_i, k_j, w_p) \quad (3.4)$$

$$| i = 1, 2, \dots n$$

$$j = 0, 1, 2 \dots n - 1$$

$$n \in \mathbb{N}$$

Each partition is made up of two airfoils joined by a surface. The airfoils are generated using third-order Bezier curves. The same partition template is used for horizontal tail, vertical tail and canard. Since the airfoil is parametrically defined, it can be used to obtain "N" number of airfoil shapes [26]. Different types of winglets and wing tip devices can be chosen (Figure 3.8). The wireframe is first instantiated and later number of wing partitions are instantiated. The projected areas of each partition are summed up automatically to give the final area of the wing and winglets.

Establishing wing partition

$$w_p^i := f(B(t), \Gamma, \phi, \theta) \quad (3.5)$$

$$| i = 1, 2, \dots n$$

$$n \in \mathbb{N}$$

$$B(t) = (1 - t)^3 P_0 + 3(1 - t)^2 t P_1 + 3(1 - t) t^2 P_2 + t^3 P_3 \quad (3.6)$$

$$t \in [0, 1]$$

$$[\Gamma^i, \phi^i, \theta^i] \in \left[-\frac{\pi}{2}, \frac{\pi}{2} \right]$$

3.1.3 Engine Design

Two types of engines (Figure 3.9) turbofan and turbojet can be sized in RAPID. Thrust, Specific fuel consumption (SFC), Weight, Length, Diameter and By-pass ratio are the key parameters that size the engine. Turbofan engine is sized to suit commercial aircraft engine dimensions

Figure 3.8 *Different types of Winglets [27].*

with a bypass ratio from 3 to 20; turbojet engine to suit the dimensions of business jets and military engines with no after burner engines with a bypass ratio from 0.1 to 15.

Nacelle geometry design depends on the type of engine and various parameters that can be changed to obtain the desired contour. Mixed-flow and separate-jet are two kinds of nacelles available; straight and smooth pylon types can be chosen. Nacelle design depends on the type of engine and various parameters can be changed to obtain the desired contour. Pylon is designed in contest with nacelle, start and end values are changed accordingly. Air inlet and duct for military application is a work in progress.

Figure 3.9 Turbofan (left) and turbojet engine (right) [V].

3.2 Interior Design

Comfort is the privilege that a passenger craves for while travelling. Aircraft Interiors is a major part of the Aircraft Design process. Cabin space has to be utilized in a intelligent fashion using most of the space, identifying the comfort factors for passenger, able to accommodate the maximum number of passengers according to the requirement. FAR 25 rules [28] have been implemented in cabin design.

3.2.1 Cockpit Design

The cockpit design consists of windshield design, cockpit layout and ergonomic study. Flat panels and blended windshield can be generated. The wing shield uses the visibility pattern as the wireframe and later number of panels can be instantiated shown in Figure 3.10.

Figure 3.10 Cockpit and Windshield model [29] [VI].

3.2.2 Cabin Layout

Seating layout, doors, windows, galley, lavatory and containers can be configured from the cabin interior layout. FAR rules have been applied to all the entities listed above. The overall length of the cabin needed is computed and the user will know the cabin length available at all times. Depending on the number of passengers; type of galley, number of galleys, number of trolleys in each galley and number of food trays needed are computed. The weights of first class, business class and economy seats are computed after instantiation.

Figure 3.11 *Cabin Layout Interface and Cabin Interior.*

"Design is not just what it looks like and feels like. Design is how it works." - Steve Jobs

4

Data Management

Data created in RAPID or Tango can be delivered in the *"eXtensible Markup Language"* (XML) format [30]. XML allows applications to represent electronic documents or text data in an easy to understand and transferable format between programs. XML is made up of markup tags and data to represent the information. An XML forms a tree structure, this makes it easy to retrieve data and find relationship between different information represented in the XML.

Figure 4.1 XML data flow between the two main applications RAPID and TANGO with the help of XSLT.

Transformation of XML document is performed by XSL Transformations (XSLT). XSLT uses XPath language to navigate in XML documents. It can serve for complex translations such as element and attribute editing (add, remove, replace), rearrangement, sorting, perform tests and make decisions [30].

The functional approach (Figure 4.1) is different in RAPID and Tango as the fundamental design approach varies in CAD and technical com-

Figure 4.2 Data communication with different subsets of geometry.

puting/programming language. Data created is translated between the programs using the data translator. In Figure 4.2 dataset 'A' of the initial geometry representation (Figure 3.5) is available in both programs. Later dataset 'B' is added in Tango and is updated in RAPID. It is to note that dataset 'C' created in RAPID is split into two subsets in Tango; for example:- wing and the engine housing are in the same geometrical product in RAPID but this is split in Tango as geometrical and functional subsets. Detail design or design add-ons to the geometry are not updated in Tango.

4.1 RAPID XML Export

Excel Visual Basic for Applications (VBA) [31] is used to configure the CATIA parameter or geometrical sets and generates into an XML. The following steps are implemented in creating XML from RAPID

- Configuration of Parameter and Geometric sets through Excel: Configuring the parameters through Excel will reduce the effort of adding changes to the code whenever a new parameter/geometrical set need to be added to the XML. The configuration contains three main parts in Excel:
 1. Parameter String: represents the parameter set/geometrical set from CATIA. All the parameters within the parameter set will be made as XML. Example: "reference\inputparameters" (Figure 4.3)

2. Parameter Array: used for making XML tags to the parameter sets or geometrical sets and parameters. Depending on the depth of the XML tree, number of values in the Array String is needed. Example: XML node - `<part name=reference>`. (Figure 4.3)
 3. Array List: Needed to put together parameter sets from the same part into one list. Each part will have one corresponding Array List. Example: `"fuselage\inputParameters"` and `"fuselage\instantiatedGeometry"` should come under the same part fuselage in XML. So they have same array list Name `fuselageList`. (Figure 4.3)
- List "Hash" [32], is a dictionary object (key, value) that is used in the code because of the Array List column that comes from Excel. The Array List column gives only Array List Names but does not create them. This handles the grouping of the parameter sets with the same Array List into one list instead of separate ones. For the first time an array list for a given name is created, thereafter it does not create a new array list if the name already exists.
 - Value Parsing: To parse the CATIA parameters and translate them to XML, two loops are used: The outer loop runs through all the parameter lists from CATIA and inner loop, runs through the parameter list of the Excel sheet. Strings from CATIA are compared with strings from Excel and the matching strings from CATIA are created as XML document.
 - Writing into XML using DOM Object: For efficient XML editing, Microsoft XML DOM object is used in the VBA section to translate the parameter/geometric sets into XML. The DOM object creates the XML file and takes care of the formatting and structure. This data set tree related access method also helps in modifying the XML without any hassles or cumbersome coding.
 - Spline from CATIA to XML: The spline in CATIA cannot be handled similar to that of the rest of the parameter/geometrical sets, as the coordinates of the points in the splines are not available directly in CATIA tree. The geometrical set in CATIA is taken as a parameter string from Excel, where the sketches are added. One array each is used to store the x, y, z coordinates of

the spline control points from the `exchange` Curves. Example: `"fuselage\exchangeCurves"` (Figure 4.3)

- Finally the XML DOM object is written to file and saved as XML.

4.2 XML to RAPID Import

The following steps are performed to read XML to RAPID:

- Parsing the XML using DOM object: The XML file is loaded into a DOM Object. This DOM object is parsed for the required information and tags.
- Recursive Function to get child nodes: The values of parameters that need to be updated into CATIA are stored in the child nodes with a `value` tag. A recursive function is used to get all the child nodes with a `value` tag from the XML and the corresponding text in these nodes. These texts are the new values to be updated.
- Constructing the Parameter Strings to be updated: The parameter string that needs to be updated in CATIA needs to be constructed; a recursive function is used to get the parent nodes for the child nodes with the `value` tag. These parent node tags are appended along with `"\"` to form the string.
- Spline from XML to CATIA: The existing spline is deleted first. The spline values in XML are stored as Control Points with x- and y-value Nodes (`xvalue`, `yvalue`). These Nodes are recursively read using DOM object. Using these x/y points, new Control Points are formed and then a new spline is created in CATIA.
- Updating CATIA: The parameter Strings along with the corresponding values are updated in the CATIA using VBA-CATIA Functions.

Figure 4.3 The RAPID-XML Interface.

4.3 Tango XML

Figure 4.4 Data Structure adapted towards the tools needs (Right side: Tango XML, Left Side: RAPID XML).

Tango uses the inbuilt Matlab Java DOM application classes for XML data rendering. The data is handled via object oriented geometrical or functional classes where every class has included class-related XML parsing functionalities. This method allows for greater flexibility and fast replacement or appending of new classes.

The elementary classes are product\geometry related (e.g., wing and

underlying wing partition class), whereas the higher level classes are product-functional (system) related (e.g., fuel system, primary flight control system). This class reference transition within the dataset makes it necessary to work with part pointers in order to link the functional classes with its related geometrical properties in the geometry related classes; Examples are the control surfaces (geo. def.) that are part of the PFCS (sys. def.) and the wing fuel tanks (geo. def.) that are part of the fuel/propulsion system (sys. def.). By these links, the strict hierarchal XML (tree) data structure becomes extended by cross-branch couplings, described by the part pointers. XML document of both Tango and RAPID is presented in Figure [4.4](#)

"Eventually everything connects - people, ideas, objects. The quality of the connections is the key to quality per se." - Charles Eames

5

Design Space

Information is congregated in the product from the conceptual design to detail design; in this case the RAPID/Tango model saves a lot of data about the aircraft. The initial design defined by the skeleton in Figure 3.5 is a design point in the design space obtained from the initial requirements.

Table 5.1 *Number of parameters for aircrafts in Figure 7.1 and Figure 7.2*

CAD Parts	Number of Parameters		Total number of Parameters	
	Wireframe	Surfaces	Civil Aircraft	Military Aircraft
Fuselage	93	108	201	201
Wing	93	108	201	201
Horizontal Tail	18	46	64	64
Vertical Tail	18	46	64	64
Canard	18	46	-	64
Engine Civil	11	34	45	-
Engine Military	11	50	-	66
Total number of parameters			464	549

To measure the robustness and flexibility of the geometry, three tests were conducted on the same kinked wing of civil aircraft (Figure 7.1).

modeFRONTIER[®] [33] was used to compute different designs.

Table 5.2 *Wing test case setup*

Design Pa- rame- ter	Ref	Wing Test 1		Wing Test 2		Wing Test 3	
		Min	Max	Min	Max	Min	Max
AR	9.71	4.71	14.71	0.7147	18.71	0.7147	18.71
TR Outer Wing	0.14	0.09	0.19	0.04	0.24	0.04	0.24
TR Outer Wing	0.14	0.09	0.19	0.04	0.24	0.04	0.24
TR Inner Wing	0.53	0.13	0.93	0.03	1.03	0.03	1.03
kink Posi- tion	6407 (0.3812)	5907	6907	5407	7407	0.3212	0.4407
wing Area	116.32	66.32	166.32	16.32	216.32	16.32	216.32
sweep Inner Wing	21.43	-28.57	71.43	-43.57	86.43	-43.57	86.43
sweep Outer Wing	21.43	-28.57	71.43	-43.57	86.43	-43.57	86.43

Design of experiments was created using Latin Hypercube sampling to obtain values that are relatively uniformly distributed for each input parameter as shown in Table 5.2. Robustness and flexibility of the design are also computed [34] as shown in Table 5.3. In “Wing Test 2” the designs have failed because the kink position is placed outside the wing for minimum values of Aspect Ratio (AR) and wingArea (Table 5.2). The Robustness in “Wing Test 2” is affected by poor parameterization of the kink position, to improve robustness of the model kink position could be given as a ratio of the span of the wing. “Wing Test 3” was

conducted with the same span of the wing as in “Wing Test 2”, so that the design space is the same. It can be seen from Table 5.3 for “Wing Test 3” the flexibility and robustness of the model has increased. There were only 31 of 2000 designs that have failed in this case. It has been observed that the failure of these designs occurred for values of “sweepInnerWing” and “sweepInnerWing”, at angles closer to 85 degrees and above. The robustness of the model increase considerably by having the kink position a ratio of the span.

Table 5.3 *Robustness and flexibility for a kinked wing*

	Number of Designs	Number of Parameters	Design Space	Robustness	Flexibility
Wing Test 1	1000	7	13.59	1	13.59
Wing Test 2	2000	7	19.33	0.751	14.52
Wing Test 3	2000	7	19.33	0.985	19.04

Design space in Table 5.3 is affected by the number of design parameters involved in the process; it would become very large once all the parameters in Table 5.1 are used to compute the design space. The normalized sensitivity matrix is shown in Table 5.4, wingArea and AR are the two parameters that mainly affect the system characteristics or output parameters of the wing.

Table 5.4 *Normalized Sensitivity Matrix*

	Design Parameters				
System Characteristics	Aspect Ratio	TR Outer Wing	TR Inner Wing	kink Position	wing Area
middle-Chord	-0.24	-0.10	0.00	-0.37	0.61
rootChord	-0.24	-0.10	-1.01	-0.38	0.61
tipChord	-0.50	0.88	0.00	0.00	0.50

In RAPID, as the user has different reference area methods, this might be difficult to pick the correct method. A number of parameters are

accessible for the user in order to obtain various configurations. This might lead to a geometry that is over-defined or has a lot of parameters to play with.

"We can't solve problems by using the same kind of thinking we used when we created them." - Albert Einstein

6

Optimization Frameworks

This section presents the multidisciplinary design and optimization frameworks that are included in this thesis.

6.1 Framework with adapted scripts for optimization

The framework presented in Paper [I] integration has been made between CATIA, Tornado and Dymola by a customized interfaces to provide an automatic interaction between these disciplines. The user interface connecting CATIA control surfaces is as shown in Figure 6.1. Parameters such as root chord, tip chord and length of the control surface are modified and updated. Inboard flap, Outboard flap and aileron can be updated to both high wing and low wing aircraft, while the elevator can be updated with respect to both T- tail and conventional tail configurations. The values of the above mentioned components can be sent to Tornado to update the aerodynamic model. The Workbook is divided into the following Sheets:

- Design Parameter sheet for all models are connected and used in the proposed framework. The design parameters allow users to modify the models without having to enter the tools that are used for their construction.
- Force Parameters sheet contains forces obtained from the Aerody-

dynamic model and are updated in the Dynamic model.

- Mass properties sheet is used to obtain the mass properties from CATIA and update them in the Dynamic model.

The Dymola model used in this framework simulates the dynamics of the control surfaces and computes the force needed to extend the flap.

Figure 6.1 *Tool Integration using scripts for Optimization*

6.2 Framework with commercial software for optimization

The framework (Figure 6.2) presented in Paper [II], the optimization was implemented using modeFRONTIER. Integration was made between RAPID, Tornado and CAVE. Using the commercial software to integrate different tools makes it easy for the user as he/she need not concern about writing the scripts to connect these tools as presented in Paper [I].

- Aerodynamic model obtains the geometry from RAPID and the simulation is performed to obtain the coefficient of lift and drag.

- These values are used by CAVE to perform the dynamic simulation to forecast the power consumption and dimensions of the actuator for a specific flight profile.
- The dimensions obtained from the dynamic model are then check in the geometric model for the placement of the actuator and available space.
- Surrogate models were created for the optimization using Anisotropic Kriging method from 300 Uniform Latin Hypercube (ULH) samples. The error between the actual model and surrogate model was 0.05 % for both Geometric model and aerodynamic model and an accuracy of 98.9 % was obtained from the dynamic model.

Figure 6.2 Tool Integration using modeFRONTIER for Optimization

Figure 6.3 Integrated Aircraft Design Network

6.3 Framework with common database for optimization

The framework (Figure 6.3) presented in Paper [IV], shows different tools RAPID, Tango, Tornado, Hopsan, Dymola and BeX integrated and have common database. The foremost objective was to have two tools Tango and RAPID work in parallel and the user could shift between the programs and the data should be able to exchange between the programs as presented in Paper [V]. Within this framework, traditional handbook methods ([35], [36] and [37]) are employed in the design.

The flow of data between each discipline in a multidisciplinary design

environment is coupled and saved in XML format [38], [39] and is accessible by all the required tools. The database definition (including several component libraries like functional assemblies) is parametrically defined in such a manner that a data refinement over time alongside the project is possible. In this way, a transition-less process from low or medium fidelity (in e.g. Tango) up to high fidelity (e.g., in RAPID) is realized as shown in Figure 6.3. Simulation models can also be generated out of the (mainly geometry) XML aircraft description . Optimization case is currently in progress

"High achievement always takes place in the framework of high expectation." - Charles Kettering

7

Applications of RAPID

Application examples of RAPID and Tango are presented. RAPID has also been implemented in academia in a couple of courses at Linköping University, the implemented examples are also presented.

7.1 Data translation RAPID/Tango implementation

This section shows the application examples of the framework, showing the data build up and data translation between RAPID and Tango and vice versa. Two examples have been tested to investigate the data flow processed in the correct approach. In RAPID, as the user has different options of reference area, this might be difficult to pick the correct method. A number of parameters are accessible for the user in order to obtain various configurations. This might lead to a geometry that is over-defined or has a lot of parameters to play with.

7.1.1 Civil Aircraft Example

In this example the double delta reference method is used(Figure 7.1). The cross-sections of the fuselage range from a circle to an ellipse. The data was successfully exchanged in both ways.

Figure 7.1 Civil Aircraft in *Tango* (top) and *RAPID* (bottom).

7.1.2 Military Aircraft Example

A much complicated fighter aircraft was selected to test as shown in Figure 7.2. Data exchange showed promising results. It is to notice that the data structure in the background of both examples is similar with modified parameters with added lifting surface "canard" in the fighter example.

Figure 7.2 Military Aircraft in *Tango* (top) and *RAPID* (bottom).

7.2 Academic Implementation

To test RAPID and get feedback, the framework has been applied as a "real world test" within undergraduate student courses / aeronautical

master courses at Linköping University.

7.2.1 The Jet Family Project

RAPID was used in the course “Aircraft Conceptual Design” to design a family of turbofan powered aircraft, according to FAR 25 rules. The aircraft family includes three family members with a seat capacity ranging from 75 to 110 (design payload) at 32 inch pitch, but high density versions had to allow for two more rows of seats at a seat pitch of 28 inches. Additionally a two class layout with 15% business seat capacity for every family member had to be studied with a seat pitch of 34/30 inches (business/economic class). The aircraft family had to be equipped with one and the same wing. The assignment also includes a study on how an optimal designed aircraft should look like (for each family member) and how much the weight and efficiency is deteriorated by keeping the wing unchanged. Interior design for this assignment was very important (as for all civil designs) as it leads to the length of the cabin. It also includes a study on the number of doors and sizes required for each family member. Number of cabin crew required, galleys and toilets for the different aircraft family members has to be figured out. The space required at the emergency exits for evacuation, accessing passenger luggage and cargo on the aircraft needs to be addressed. Also, it is required to consider all kinds of ground handling while on the ground, i.e. the possibility to service the aircraft by means of different vehicles during ground stop.

It is also important to provide the required spacing at the emergency exits for evacuation. Number of toilets, galleys and the number of cabin crew required for the different family members also needs to be figured out. Where to put and access passenger luggage and cargo on the aircraft needs to be addressed. Also to consider all kinds of ground handling while on the ground, i.e. the possibility to service the aircraft by means of different vehicles during ground stop.

- Mdes : 0.82 at 35000 ft for all family members
- Range : 2500 NM at design payload for in-between member of the family
- Reserves : 200nm + 30 min holding
- T-off field length (SL, ISA +20) max : 1900 m for all members
- Landing field length (SL, ISA +15) max: 1500m for all members

Figure 7.3 One of the student aircraft and interiors with two class seating configurations and an artistic view of the aircraft..

- Individual passenger weight (including luggage) : 110 kg
- Pilots including personal luggage : 104 kg each
- Attendants (including personal luggage) : 100 kg each

7.2.2 The Mid-Jet aircraft Project

The Mid-Jet project was to build a aerobatic, aesthetic, striking and overwhelming single seat sport jet. To test and demonstrate the flight performance and characteristics a scaled model had to be built. As a first part of the project, a study of existing single seat sport jets was conducted and different concepts were proposed. These ideas were studied from each student team and finally the best concept was chosen for further studies. This concept was then developed in RAPID up to the conceptual design stage for the full scale version of Mid-Jet. From this, a subscaled version intended for the practical design was developed up to the detailed design stage by adding different features to the RAPID model successively. With this model, a demonstrator on a scale of 1:2.8

was built and successfully flight tested. It is to note that the period between the first design studies until the maiden flight of the demonstrator had only been ca. six months. Particular attention was paid in order to detect the usability of the conceptual/ preliminary design model within the detailed design stage.

Figure 7.4 *Mid-Jet aircraft project process.*

7.2.3 Very Light Jets(VLJs)

The VLJs project was to design a two-seater and the other a four-seater aircraft. Both the aircrafts were to be designed around DGEN-380 engine. The aircrafts should be flown by normal, average skilled pilots e.g. flying club members. The altitude for the flight was below 20000 ft and the cabins were not pressurized. Main design solutions were presented including seating arrangement, structural layout, entrance door placements and design, engine placement, placing fuel, baggage and basic landing gear design. Weight and general performance of the aircrafts were evaluated along with center of gravity range, stability and trimmability. The artistic view of the aircraft designed in RAPID by the stunts are shown in Figure 7.5.

Figure 7.5 Artistic view of students Very Light Jets; Single engine 2-seater (Left), Twin engine 4-seater (Right).

"I have not failed. I've just found 10,000 ways that won't work." - Thomas A. Edison

8

Conclusion

Aircraft Conceptual design is an iterative process. The designer needs to gain an overview of the aircraft geometry appearances and the design changes that occur during the design process. The geometry plays a major role in the design process and it is needed to be represented in a CAD environment to carry forward to the next level. The geometry created during the processes is desired to change rapidly and also the changes to the geometry need to be realized immediately. KBE methods implemented in early design phases will assist in a wide range of studies that can be conducted with the design and help in the rapid realization of a concept generated during the design process.

The Knowledge based engineering approach is recognized for using in conceptual design. This will facilitate the propagation of the geometry from conceptual to preliminary design. The RAPID tool is developed to aid in the quick geometry creation and eventually studied for a better understanding of aircraft concept. The geometry obtained in RAPID has a very high degree of detail to obtain a wide range of aircraft configurations. A watertight model can be obtained to transfer the geometry to CFD. Effective parameterization is implemented and it is significant for enhanced construction with RAPID. Different fidelity in the geometry can be utilized at the respective stages depending on the need and purpose.

A geometry created in CAD environments encloses a lot of data, e.g. design parameters for creating the concept aircraft, geometrical parameters, etc. Data increase as the design is building up, to save the data and to have a better communication of data with different disciplines an XML database is constructed. This method allows for direct access

of geometry for other tools, like a geometry optimization outside the CAD environment. Even simulation models could be generated out of the description in XML data. Geometrical data has been successfully implemented between RAPID and Tango.

Different optimization frameworks have been reflected, each framework is different from the other in method and implementation. Different disciplines for the optimization are unified using customized scripts. An enhancement is done by using commercial software for optimization using meta models. The use of meta models for optimization has reduced the time required for optimization and the different experiments could be conducted on the same geometry. A framework is also presented using the XML data setup, supporting in sharing the data with a large group of people for greater collaboration. One tool vs. one database has been discussed and one-database concept is proven to be more effective as each tool is specialized in a specific environment.

"The true method of knowledge is experiment." - William Blake

9

Outlook

RAPID as a tool is implemented in academia in different courses, nevertheless, the framework needs to be validated in industry. Further work to effectively distribute the geometry for different disciplines such as aerodynamics, structures etc. needs to be studied and applied. Future work in RAPID includes weight estimation, drag calculations and optimization framework. Improvements in the existing structural model and aerodynamic model are needed to update the mesh automatically so that it can be used in optimization framework. Aircraft systems integration is needed to estimate the volume available for best fit of the components. Some research question need to be answered in future are as follows:

- What methodologies can be applied to break down the structure of a geometric model in CAD environment for making it more robust and speedy update?
- How to make sure that there exists a C2 continuity between the surfaces after the instantiations in RAPID and how can it be measured?
- In what way can the geometry of aircraft systems be implemented in the early conceptual design?
- Is it advantages to adapt methods like fuzzy logic and neural networks in conceptual design for knowledge-based integrated multi-disciplinary optimization?
- In what manner can the database be used effectively without using

the geometry in knowledge-based integrated multidisciplinary optimization?

"Knowledge is not simply another commodity, On the contrary, Knowledge is never used up. It increases by diffusion and grows by dispersion. "
- Daniel J. Boorstin

10

Review of Papers

This section presents a short summary of the Papers [I] [II] [III] [IV] appended in this thesis.

Paper I

Model Based Aircraft Control System Design And Simulation

An optimization framework is developed for aircraft conceptual design by connecting different disciplines such as CAD, aerodynamics, dynamics with customized scripts. The optimization case is performed to visualize the automation capability of choosing an actuator from the database to enhance the early phases of conceptual design.

Paper II

Multidisciplinary Optimization of Aircraft Vehicle System for Conceptual Analysis

An optimization framework is built using modeFRONTIER for RAPID , CAVE and Tornado. Each tool in this framework has a different purpose; RAPID is used for geometry generation, CAVE for dynamic simulation and Tornado for aerodynamic simulation. These tools are connected and an optimization is performed using meta models. It also shows that the time for an optimization is reduced drastically by using the meta models.

Paper III

RAPID – Robust Aircraft Parametric Interactive Design: A Knowledge Based Aircraft Conceptual Design Tool

RAPID as a tool is presented in this paper. The design methodology followed in building the geometry is explained. Application examples in academia are presented showing the capability of RAPID for conceptual design.

Paper IV

Integrated Aircraft Design Network

RAPID, Tango, Tornado, Hopsan and Dymola have been integrated using the one-database concept. XML document is structured and human readable. The methodology used to create the XML document is presented along with application examples that were tested between the two tools.

"If you can dream it, you can do it." -Walt Disney

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Papers

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