Abstract

This work presents knowledge-based parametric definition of aircraft fuel systems, oriented to its use in conceptual design and integrated into the RAPID design tool. Fuel systems appear early in the design process as they are involved in several first estimations. For instance, fuel weight is a significant part of take-off weight and decisive in aircraft sizing and range estimations. Therefore, including fuel systems earlier in the design process creates an opportunity to optimize it and obtain better solutions.

1 Introduction

The use of CAD methods is extended to most of the aircraft design process, yet the conceptual design phase has singular requirements that don’t match the usual concept of these tools. Conceptual design is often an iterative process where the designer’s ideas need to be defined in a fast way and therefore the level of detail of the design is often kept to the minimum. However, it is also highly multi-disciplinary as the designer or designing team has to take into account several disciplines such as aerodynamics, structure or system integration. As detail and exactitude of 3D modeling do not look like a great advantage that could compensate the time employed in it, conceptual design also covers weight estimation, aerodynamic calculations, payload and range requirements that will be repeated several times and it is advantages to have the CAD model for better prediction.

RAPID (Robust Aircraft Parametric Interactive Design) is a knowledge-based aircraft geometry design tool that is being developed at the Division of Fluid and Mechatronic Systems of Linköping University [1]. This project is a continuation in line of work with integration of functional systems in RAPID [2] as aircraft systems integration is needed to estimate the volume available for best fit of the components [1].

Parametric design seeks for fast as well as a flexible definition of the CAD model while the knowledge template concept is useful in a multi-disciplinary environment as each specialist can transfer his experience and knowledge in the tool for the rest of the design team to use it.

Fuel capacity is directly related to range performance, one of the basic requirements when designing a new aircraft [3]. In the same way, position of the fuel tanks has a big influence in balance and therefore maneuverability, influencing in take-off and landing distances. Even though, fuel system considerations are traditionally placed in the preliminary design phase [4] yet new tools can change this tendency.

2 Objectives

The goal is to take advantage of CAD in the early stages of aircraft design by allowing the designer to define the fuel system with parameters and consequently be able to measure fuel capacity or see fuel tank’s position and a first outline of the fuel system in a 3D model.

The project followed the steps stated below in order to achieve the main goal:

1. Plan how to represent the main functions of fuel systems in civil aircraft:
• Engine feed.
• Fuel transfer.
• Refuel/defuel.
• Tank venting.

2. Create templates that represent the geometries of the main components of the fuel system in a flexible way.

3. Use Knowledge Pattern to instantiate these components in a preexisting aircraft geometry defined in RAPID.

4. Use parameters to modify the general layout of the components in the system.

5. Connect the defined components in the fuel system regarding the preexisting aircraft geometry.

6. Use parameters to take measures of variables that can be useful in conceptual or preliminary design.

3 Simplifications

The target application of this fuel system model is conceptual to preliminary design. In addition, aircraft designers need enough flexibility to define new ideas and cover several types of aircraft and configurations. Therefore some simplifications were made in order to create this model in an optimum way:

• All geometries are symbolic, representing a space allocation inside the aircraft for the fuel system. They are not a realistic representation of real components as that task can be realized in detail design.

• Smaller geometries as valves or fuel intakes inside the tanks are not represented.

• Fuel quantity measuring system is not included as it is a challenging design task complex to automatize and occupies a small space compared with other system functions.

• Symmetry is applied in the whole system, but both sides are represented.

• Fuel tubing or piping is often represented with direct lines between two pumps or tanks and represent the minimum length needed of this component. An exception for this is the pipe connecting fuel tanks from the tail to the fuselage, which was represented with more detail.

• Wing and horizontal stabilizer spars are represented as surfaces limiting the tanks, as a structural model integrated in RAPID was still being developed during the realization of this work.

• Only representative fuel system layouts are represented in this model, as there can be a big number of layout alternatives used in the industry.

4 Development of Fuel Systems

This section describes the fuel system integration in the RAPID tool from a tool designer/programmer point of view, going from a wider to a more detailed view of its characteristics and ending by describing all of its components and function. Anyway, specific code and tool application examples are not included in this document. Design automation is performed using Knowledge pattern feature in CATIA® [5]. It uses a UDF (User Defined Feature), a catalog and script for instantiation.

4.1 Parametric control

At Part level, the logic that the design tool will use when instantiating the UDFs is controlled by a set of 13 parameters. Furthermore, three output parameters will give the user fuel capacity and tubing length measures and other four parameters make global changes in the instantiated UDFs to make weight balance related measurement. An example of parameter values is shown in Figure 4. At a UDF level, each component characteristics, position, shape and measurements are visible as published parameters (see Figure 3).
The number of parameters in each UDF is comprised between 4 and 25, but in the case of common values such as Fuel Density in the tanks or values determined by the system layout as for example symmetry of a specific pipe.

![Figure 1](image1.png) Part level parameters controlling the fuel system.

Three Knowledge Patterns are used to instantiate the main three functions represented: fuel storage, fuel transfer and crossfeed; with instantiation priorities as the definition of any piping is made relative to existing fuel tanks. First objective for instantiation logic is illustrated in Figure 2. The UDFs instantiated are placed inside Geometrical Sets in order to have better organization of the product tree, as seen in Figure 3 and they are also listed in their original Knowledge Pattern.

### 4.2 Component description

#### 4.2.1 Wing tanks

Wing integral tanks are represented by instantiating the UDFs `integralFuelTank`, `FeedIntegralTank`, `integralFuelTankWithRefuelStation` and `FeedIntegralTankWithRefuelStation` which contain the same base integral tank, that is defined with the wing geometry around as an input and different combinations of the presence of fuel pumps and refuel stations. All pumps used in the fuel system are defined inside the tank UDF instead of creating a ‘Pump UDF’ and instantiate them afterwards. Both solutions were discussed and by defining them along with the tank more geometric information of the pump boundaries is available. All geometries are created on the right side of the aircraft and a symmetry is applied. Several warning checks if the control parameters that the user specifies as input are logical to the model: watching ratio values, the distance between ribs, that the tanks do not overpass the boundaries of the wing and that the pumps are kept inside the wing geometry.

**Fuel storage**

This tank is defined in context with the wing skin geometry, the front and rear spars and four ribs that are sealed or semi-sealed to form the tank, the possibilities of this are illustrated in Figure 4.

![Figure 2](image2.png) Logic followed by Knowledge Pattern in the instantiation of the fuel system according to user input parameters.

![Figure 3](image3.png) Fuel systems in RAPID: product tree organization and example of UDF-level parameters.
The tank is defined using 11 parameters, in a way that covers the main fuel tank geometries seen in contemporary commercial aircraft (see Figure 5). This number could be reduced if a structural model of the wing was available, as geometrical data for rib positioning, thickness and angle would be previously defined, ribs would only be selected and only sealing would need geometrical definition by parameters.

Fig. 4 Two examples of integral tank geometries; with construction lines to show the definition of the tank shape.

Fig. 5 Fuel tank shapes example compared with A340 wing tanks.

Not only the full tank is represented, but also a partially full tank can be analysed. For this feature, the user specifies at Part level the attitude of the aircraft using two parameters: pitch and roll angles (as yaw angle does not affect the fuel surface in the tank); and the volumetric fraction of the fuel, that can be different for left and right tanks. To work with volumetric fraction as a more intuitive parameter to define the fuel surface, an iterative method (‘regula falsi’) was implemented. This method basically moves the cutting plane that defines the fuel surface along the vertical axis until the desired fraction is represented.

The intention with the representation of partially filled tanks is to use it in stability analysis, as it affects the center of gravity and to position vent points and inlet lines for fuel pumps (see Figure 7). The tool also outputs, in the form of parameters, measures of fuel capacity (volume and mass, as fuel density is defined by the user at Part level), fuel volume when the tank is partially filled and it sums up capacity from the wing tanks that will be used to tell the user total fuel system capacity.

Fuel transfer

Only the more common types of fuel pumps in commercial aviation have been represented in this tool, centrifugal pumps with the following configurations: cylindrical and skin mounted; cartridge-canister and skin mounted; front spar mounted. Examples for this can be seen in Figure 6.

Fig. 6 All types of centrifugal pumps the tool is capable of representing: A) cartridge-canister; B) cylindrical; C) spar mounted.

In this case, fuel transfer pumps cannot be spar-mounted type, therefore they can symbolize two types of centrifugal pumps: cylindrical and cartridge-canister configurations. Transfer pumps are defined with 4 parameters of pump geometry and 2 parameters for positioning, using
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rear spar as a reference in order to separate them from the feed pumps that will be placed near the front spar, most likely the position closest to the engines. They are always placed in the bottom of the tank.

**Engine feed**

Feed pumps can be of all types. They are defined with one parameter for pump type selection and another parameter to make redundancy in feed pumps, a common request for ETOPS regulations; 6 parameters size and position the pump and another one positions the second pump when redundancy is selected.

**Refuel system**

One refuel station for the aircraft can be added with one parameter at Part level. It is situated in the right wing as commercial aircraft are usually loaded from the left side and consists in a simple rectangular representation placed in the bottom of an integral tank.

**Fuel storage**

A main central tank is defined by its position relative to the wing reference planes and origin point. Then the next tanks are placed with reference to this tank, forward or after on the fuselage. This will allow the user to chose which tank is the feed tank, in this case the reference one. The tank geometry is basically rectangular, as it is commonly used for fuel quantity measure reasons [6] [7]. In the case that the designer wants to use the most of the space available, the fuel tank is cut by several geometries: the inner surface of the fuselage and the central wing box. A check watches if these tanks are cut or not by the fuselage and informs the user using a parameter. The UDFs takes different measures: minimum distance from the tank to the wing box and to the interior floor and fuel capacity volume and mass). This tank can also be represented partially filled, so fuel volume is measured.

**Fig. 7** Fuel system representation in fuel tank including: fuel tanks partially filled (aircraft has a positive pitch angle), surge tank, refuel station, transfer system, engine feed pumps (redundant) and crossfeed piping.

**Fig. 8** Example of fuel tanks placed in the fuselage of the aircraft.

**Engine feed**

Fuel system in this tool was conceived to represent aircraft with one to four engines. In the case...
that the aircraft has an odd number of engines, the central tank will act as feed tank for the central engine. Feed pumps are specified in the central tank and crossfeed connections connect to it. In fuselage tanks, fuel pumps cannot be fuselage mounted but the other two types. A Rule depending on a parameter is used to activate redundancy of the feed pumps when it is specified by the user. When redundancy is activated, one pump is symmetrical from the other with reference to the aircraft symmetry plane.

\textbf{Fuel transfer}

Fuselage tanks are the most influential on the position of the aircraft’s center of gravity. The designer can use the fuel mass measured by the tool in a parameter, and use CATIA integrated features to measure the fuel’s center of mass. This can be used mainly in both stability and control analysis, and when designing the fuel management control unit behaviour. Transfer pumps are placed in the symmetry plane of the aircraft but can be moved and shaped using 5 parameters.

\textbf{Fuel storage}

The stabilizer surface and the rear spar inside it are the inputs for the UDF used to limit the tanks. Normally, the integral fuel tank cannot be aft from the rear spar as the actuators from the control surfaces are placed there. These are the tanks defined with less influence in fuel capacity. However, their position in the extremity of the aircraft’s longitudinal axis makes it noteworthy when analysing pitch moment and aircraft stability.

As in the rest of the fuel system, tanks can be represented partially filled and the tool measures on fuel capacity (volume and mass) and current fuel level.

\textbf{Fuel transfer}

Transfer pumps can be placed everywhere in the tank given that they are always attached to the floor of the tank. Pumps are symmetric and a check informs the user if the given pump is cut by the limits of the tank.

\textbf{4.2.4 Crossfeed piping}

Crossfeed is a basic function of the fuel system, as aircraft in a situation where one or more engines have stopped needs to be able to use all the available fuel. Three UDFs have been defined to add a symbolic connection between the different feed pumps the aircraft may have: \textit{basicPip-
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ing, 3pointPiping and basicPipingSparMounted, the last mentioned having a correction in orientation when connecting spar-mounted pumps. They consist in a direct tube that will connect two feed pumps, representing the minimum distance of tubing that specific configuration needs. In order to make a more realistic representation, better solutions lay in specific CATIA workbenches as System routing, Piping design and Tubing design if automation can then be implemented.

**Fig. 11** Crossfeed piping shown in orange; connecting four feed tanks with pump redundancy. Transfer piping is shown in green, including the aircraft’s refuel station.

**Fig. 12** Detail of 3-engines configuration, where 3pointPiping UDF is used.

Four configurations (one to four engines, therefore one to four main tanks and feed pumps to connect) are represented, selected by the user with a parameter at Part level as seen in Figure [13]. One parameter at Part level measures the length of the piping segment, which is after added up to show the system piping length needed. Checks are added to inform the user that other geometries could be cutting the piping but they are informative and only the user decides if the result is correct.

**4.2.5 Transfer system piping**

This subsystem connects every tank of the aircraft, more specifically all its transfer pumps, and includes the refuel function in it, having connected the refuel station of the aircraft as it can be seen in Figure [11]. In addition to basicPiping and 3pointPiping, a UDF called tailPiping generates a specific pipe to connect the tail tanks, which uses three checkpoints to define a path for the pipe that avoids the passenger cabin. This is shown in Figure [14].

**Fig. 13** Indication by the user of the engine configuration with a parameter at Part level.

**Fig. 14** Fuel transfer system connecting an aft fuselage tank to the tail tanks.
4.2.6 Tank venting

The venting subsystem is represented symbolically, consisting in two surge tanks outboard of the wing tanks and a rectangular surge box (where the lightning protection lays) that the user can modify in size and position that includes a symbolic NACA inlet in the bottom of the wing surface, making the surge box easily recognizable for the designer. The subsystem can be seen in Figure 11.

5 Discussion and Conclusions

During this whole development of the fuel system model, the ultimate goal is to make it useful to a designing team.

Thinking in the user experience, a balance between automation level and flexibility was an important decision in every functionality added to the model and the number of parameters needed for the system definition can sometimes make the tool difficult to the user. The way of visualizing or classifying the parameters and a memory of used values could enhance the user interface.

From my point of view, this method could be much more effective in a company in-house design tool compared to its use at university level, as design has more constraints given that the applicable components of the fuel system are usually limited by several factors:

- Previous knowledge on how to design the system would be firstly implemented in the tool. Previously applied methods are often safer and cheaper [4] and the tool would become a way for discipline experts to share their knowledge with the rest of the company.

- During conceptual design, a decision on what new technologies will be incorporated is made as emerging technologies can become available during the project development [3]. The design tool can become an effective way of communicating what is classified as ‘applicable technologies’ in a certain project.

- Preferred suppliers and economic factors can be reflected too by limiting the number of component variants.

Nevertheless, the next functionalities from a designer’s point of view were successfully implemented in the RAPID tool and are the most relevant results from this work:

- Fuel capacity estimation based on 3D geometries, an estimation that is specially complex when working with integral tanks.

- Capacity to accurately position tanks and pumps in a fast way, with the objective to be able to work with the tool in both conceptual and preliminary design phases. A feature that can be used, for example, for space allocation or systems integration in early stages of design.

- Measurement of piping or tubing length for a simple example of transfer system architecture, a first estimation that can be relevant data for pump sizing.

- Definition of the fuel volume in different attitudes when the tank is partially filled. This feature can help to position pump inlets and venting points and to analyse the fuel influence in aircraft’s center of gravity and stability.

- Automation and parametric definition of the system, that could be translated in communication with other programs and new capabilities.

6 Future developments

RAPID tool is updated by adding new features, thus the definition of the structure in RAPID would mean parameter simplifications in the definition of the integral tanks, as it was mentioned in Section 5.3.1. Spar definition was considered and only an input name change in the Knowledge Pattern would be needed, but the UDFs would need to be changed in order to use the ribs existing in the structural model.
The objective of connecting the tool with Microsoft Excel was not fulfilled for time restrictions, but it seems a simple exercise of Visual Basic scripting as it was implemented in [2]. A better visualization of the parameters for the user and a memory of previously used values is a more complex task that could enhance the user’s experience. The model has an order of definition of the parameters: from the part parameters to the UDF parameters and following the relations between different UDFs. This means that currently in the tool, changes in reverse order will make the user defining again the parameters of the UDFs that need to be instantiated.

To conclude, a lot of possibilities are opened when having an automated, parametric definition of part of the fuel system and taking measures from it. In my opinion, connecting this automated definition of the fuel systems with an optimization program could lead to the most interesting results of this work, as currently the tool measures characteristics of the system that can be part of the optimization objective, using the model as objective function while the parameters are changed.

References