RECENT ADVANCES IN AIR-VEHICLE DESIGN SYNTHESIS AND OPTIMISATION

David A Lovell*, Catherine A Crawford and Kevin E Restrick****
***Applied Technology Consultants, **QinetiQ Farnborough**

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Abstract

Over the past 30 years conceptual design and optimisation programs have been developed and applied by QinetiQ and its predecessor organisations to study the effects on aircraft concepts of changes in requirements and advances in technology. Recent work is described that extends design synthesis and optimisation to cover a far wider range of air-vehicle concepts, and links concept design optimisation to multi-disciplinary analysis and optimisation. The design and assessment environment being evolved at QinetiQ is reducing the time required for a design / assessment cycle and providing greater flexibility in the study of concepts.

1 Introduction

1.1 Historical background

Work at the Royal Aerospace Establishment in the period 1970-80 coupled aircraft synthesis, performance analysis, and non-linear constrained optimisation to form conceptual design optimisation methods. Separate codes were written for civil [1] and military [2] aircraft applications. To ensure acceptable execution times on the computers then available, these codes were highly tailored to specific types of aircraft. The two programs formed the basis for subsequent code development at RAE, its successor organisations (DRA, DERA and QinetiQ), and Airbus, e.g. refs [3,4,5]. The considerable number of studies (e.g. ref [6]) of the effects of requirements and advances in technology on aircraft concepts that have been performed with these programs over the past 30 years has confirmed the effectiveness of the basic process. The rapid growth in computing power per unit cost in this period has enabled more complex studies to be completed more rapidly.

1.2 Current environment

Design synthesis and optimisation (DSO) methods provide the outline concept description which is used as the starting point for more comprehensive studies by technology specialists: configuration design in industry or detailed assessment by government agencies. Both classes of customer place high value on the rapid turn-round of this work. At QinetiQ the two phases of work are being integrated [7] into a generic process for air-vehicle concept design and assessment.

Efficient definition, transfer and enrichment of the initial concept geometry are critical to the overall process. Ref. 7 describes the integration of Computer Aided Design (CAD) into the process, and the aerodynamic shape optimisation of a military aircraft concept generated by the QinetiQ design synthesis method. Subsequent work at QinetiQ [8] has added finite element structural analysis to the generic process, to assess the impact of cruise speed on high-speed civil transport aircraft concepts. Thus an important requirement for DSO methods is the availability of simple, generic, geometry parameterisation schemes that are compatible with the CAD tools used for detailed design and assessment.

In considering new concept shapes CAD tools are also valuable for exploring the options for packaging the contents of the air vehicle, and thence for defining the geometric constraints that need to be included in the design synthesis.

Recent years have seen a major expansion in the variety of concept shapes that are being considered for air vehicles. Whereas in the past DSO could be based on the characteristics of existing, related air vehicles, today relevant data do not exist for many of the concepts under consideration. Reliance now has to be placed on the definition of a virtual air vehicle, shaped by detail design tools and analysed by state-of-the-art tools (e.g. CFD and FE structural analyses), to create the required data. At QinetiQ response surface methods are used [7] to permit the data from the performance analyses at the detailed level (aerodynamics, mass etc) to be distilled for use at the concept design level. Fig 1 summarises the generic process.

Because of the needs to cover a wider range of concept shapes, and to respond rapidly to evolving military requirements or to respond to changes in the market needs for transport aircraft, QinetiQ has begun to construct DSO programs based on common modules.

The remainder of the paper describes aspects of design synthesis that have been addressed recently and will feature as common modules in future programs.

2 Geometry Parameterisation

Geometry parameterisation schemes have been developed for the major components of air vehicles that are sufficiently generic to represent a wide range of concepts. The degree of detail employed enables the internal packaging of the component to be modelled, and the volume and surface area to be estimated to the level of accuracy appropriate for initial concept design.

2.1 Centre body

2.1.1 Cross sections

The geometry parameterisation developed covers two classes of body cross section. The first (blended), applicable to low-observable military air vehicles and blended wing-body transport aircraft, covers section shapes that have the body slope matched to that of the wing root at the body side. The second (discrete), applicable to most other civil and military air vehicles, has a slope discontinuity at the body side. Geometry variables are defined to describe sides that may be curved or sloped. Fig 2 indicates the wide range of sections that may be modelled.

Five of the variables determining the geometry of each cross section are treated as optimisation variables, and constraints are defined to ensure internal items can be contained within the section. Fig 3 and Table 1 show the results from minimising the cross-sectional area of two blended cross-sections while containing a large payload bay between them. The execution times quoted are for a 1-2 GHz PC processor.

2.1.2 Longitudinal sections

A simple parameterisation of the longitudinal cross section of the body, in terms of thickness and camber, has been developed that can be used to model a wide variety of shapes. Applications of this parameterisation to the body centre line section of a flying wing, a UAV and a missile are shown in Fig 4.

Ten of the variables determining the section geometry are treated as optimisation variables. Position variables and constraints are also defined for internal items to ensure that they can be contained within the section. Fig 5 and Table 1 show the results from minimising the centre-line sectional area of a flying wing concept which contains two large packages.

2.1.3 Complete body

The parameterisation for cross sections has been combined with that for longitudinal sections to provide a geometry description for a complete body. Fig 6 and Table 1 show the results from an application of this geometry in which the values of the geometric variables for the centre-line section and three cross sections have been optimised to minimise the volume of the body to contain two boxes. In addition to those controlling the body shape, variables define the fore-and-aft, and vertical positions of the packaged items. Associated constraints ensure these packages do not overlap and that they are contained within the body.

2.1.4 Application to blended wing transport aircraft

Recent work has been undertaken by QinetiQ as part of the REUTAC research programme (Rapid Evaluation of Unconventional Transport Aircraft Concepts [9]), funded by Airbus and the UK Department of Trade and Industry. Here the centre body of a blended-wing-body (BWB) aircraft has been modelled using the techniques described above (Fig.7), and implemented in a DSO program.

It is important to model accurately the layout of this type of aircraft configuration during the conceptual design phase. The novel design allows greater flexibility in the positioning of items such as the passenger cabin, cargo, and the undercarriage, compared with a conventional civil transport aircraft. Factors that need to be considered early in the design process are passenger acceptability, evacuation requirements, and accessibility for ground handling equipment.

The external geometry and the internal packages are handled independently and are sized and positioned using appropriate design rules. The code is modular so that alternative descriptions of the geometry, or more comprehensive design relationships, may be used depending on the study requirements.

The surface of the centre body is modelled by longitudinal sections across the span of the body. Three types of section can be used:

(1) analytic: a NACA aerofoil section,
(2) parametric: longitudinal thickness and camber as described above,
(3) splines for an aerofoil generated by a CFD process.

These sections offer the desired level of accuracy required for the internal packaging and the other analyses, whilst being sufficiently flexible to match the range of configurations likely to be required. The sections may be translated vertically and horizontally, rotated, and the thickness and camber of the section may be changed.

Three internal items are considered: the passenger cabin, the landing gear, and the cargo hold. These items have the greatest effect on the performance and external shape of the aircraft. The layout within the passenger cabin is particularly important because the unconventional shape of the aircraft means that passenger comfort levels, and the means of access (including emergency exit) can have a major impact on the aerodynamic and structural aspects of the design. For example, for a given cabin width, as the leading edge sweep of the aircraft body is increased, the overall length of the aircraft will increase to seat the required number of passengers. The increased length will change the structural and aerodynamic properties, and change the position of the cargo and the loading on the landing gear. This may be offset by an increase in the space available for exits, access for ground handling equipment, and passenger movement.

The undercarriage is a large package that can have a major effect on the external surfaces, and on the position and quantity of cargo that may be carried. The position of the undercarriage is controlled by the optimiser, with constraints applied to ensure a sensible design (e.g. to meet centre of gravity requirements).

The cargo hold consists of up to seven separate cargo areas, depending on the size of aircraft. The size and position of the cargo areas are allowed to vary and constraints are applied to ensure that the required clearance envelopes exist around the packaged items. A total of 46 independent variables and 35 constraints are used, typically giving a converged solution after 2-3 minutes, and 2400 function evaluations. An example of the synthesis is shown in Fig 8. The starting point at the top shows that the aircraft is long and thin, the cabin and cargo areas are too small, and the undercarriage is in an infeasible position and clashes with the outer surface. The bottom of the figure shows the shape of the centre body optimised for minimum volume. The full complement of passengers and cargo can be carried, the undercarriage is in an acceptable position, whilst the outer surface is closely wrapped around the internal items.

In addition to the longitudinal description of the body, cross sections of the body are also considered in a similar manner to that described in 2.1.1. Fig 9 shows a section tightly wrapped around the internal items. 13 optimisation variables are used for each section.

2.2 Wing

2.2.1 Geometry parameterisation

Existing syntheses at Farnborough [3] have been confined to wings of trapezoidal planform defined by 5 variables. This modelling has been found adequate for conventional swept and delta wings, but can give only a very approximate representation of many planforms used for low-observable military air vehicles and unconventional transport aircraft. Geometry parameterisation has therefore been developed for a cranked wing having up to 4 cranks, as shown in Fig 10. The wing geometry is defined by 18 variables all of which are potentially at the disposal of the optimiser.

2.2.2 Application to an unmanned air vehicle

This parameterisation has been implemented in the combat air vehicle program, the most developed of the QinetiQ DSO codes, which is capable of modelling both manned and unmanned concepts. The complete synthesis has 61 variables at the disposal of the optimiser and 89 constraints. A few constraints are optional to allow modelling of particular designs (e.g. to match a specified wing area) but most are activated in any given run.

The aim of each program run is to size an air vehicle that meets all the packaging constraints, delivers the required level of performance and has minimum mass. Data is input to the program in the form of a set of external variable values that remain fixed throughout the optimisation, and starting values for the design variables that the optimiser has the freedom to change. Also provided is a look-up table of data for an engine at a reference scale, giving thrust and fuel flow at a range of altitudes, Mach numbers and throttle settings. The engine may be scaled during the optimisation process, the scaling algorithms being chosen to maintain the engine thrust-weight ratio. The program synthesises the aircraft geometry, calculates its mass and aerodynamic characteristics (based upon an equivalent trapezoidal wing), and hence, with the addition of the propulsion data, estimates its mission performance. The optimiser changes the values of the design variables and the process is repeated until a solution aircraft is obtained, a process that takes less than 2 minutes for many thousand of iterations on a PC.

As an illustration of the use of the program, the effect of progressively introducing wing cranks on the size of an air-vehicle has been determined. The four configurations illustrated in Fig 11 have been sized to carry the same payload over the same mission profile and range. In each case the leading and trailing edge angles have been fixed (at 60°/40° on the leading edge and +/- 40° on the trailing edge), but the locations of the cranks have been allowed to vary to give the optimum planform. The point performance parameters selected as requirements (in terms of specific excess power, turn rates, acceleration times) are undemanding, and do not in general drive the designs. In each case the wing is sized by an attained turn requirement. In the baseline case (with no wing planform cranks) the engine is sized by the specific excess power requirement at the top of climb; in the other cases it is sized by the take-off requirement.

Fig 12 compares the empty vehicle masses and the fuel mass required for each UCAV to complete the mission, the values being quoted relative to the baseline case. It can be seen that as each crank is introduced the empty vehicle mass is reduced, there being a 20% reduction in mass between the two extreme planform cases. Even more significant is the reduction in the required fuel, with almost a 40% reduction between the extreme cases. These results are preliminary as the effects of the cranks on the aerodynamic and mass characteristics are not currently modelled.

As each additional crank is introduced the aspect ratio of the wing increases, causing a reduction in the lift dependent drag. With lower drag the engine can be scaled down to produce the same level of performance. The UCAV can then be reduced in size to contain the smaller engine and reduced fuel volume. The smaller vehicle then has lower drag, allowing a further reduction in size, resulting, after a number of iterations, in an optimised UCAV that is smaller and lighter to give the same performance.

3 Application of CAD

Over the past 5 years CATIA V5 from Dassault Systemes has been used extensively by QinetiQ as a common CAD tool within a multi-disciplinary assessment framework involving four disciplines: aerodynamics, structures, signatures, and conceptual design. Two key features CATIA provides, parameterisation and a knowledge-based engineering approach, make the tool particularly suited to the development and analysis of air vehicle concepts. CAD is being used in two critical areas of the work on DSO. During the development phase of a synthesis, CAD is used to support the traditional 'pen and paper' approach to developing generic parameterised geometry. CATIA provides an interactive development environment that allows greater exploration of the potential options for concept geometry. During this phase key aerodynamic or structural knowledge can be captured and included in the model. CAD can be used to validate the resulting optimised geometry in terms of calculated values such as wetted area, and provide an accurate check on the internal packaging. The detailed CATIA model forms a common product model for use by specialists in the generic process shown in Fig 1.

3.1 Vehicle outer shape

Paragraph 2.1.4 has described how a generic parameterised geometry can be applied in a DSO process for a BWB aircraft design. Because this approach is based on a generic geometry description that can define a wide range of configurations, the user has immediate access to these variants. These geometries are then available for separate studies, thus reducing the development cost for the associated synthesis.

CAD is being used to explore the design space for the parameterised geometry, and thus ensure that it covers the full range of configurations required. The parameterised geometry has been implemented in CATIA, and is driven externally by an Excel design table. In this manner the geometry may be quickly 'morphed' between shapes, as shown in Fig 13. In this figure the single geometry model defined in 2.1 and 2.2 is used to represent three very different configurations of air-vehicle.

3.2 Vehicle packaging

A key criterion in the concept definition phase of development is to ensure that there is adequate space for the internal items. This aspect of modelling is becoming increasingly important, as shown in 2.1.4 for a BWB civil transport aircraft. This is also true for military air vehicles, as these become smaller, their shapes more complex, and their contents more significant in determining vehicle shape (e.g. sensors and communication devices). The ability to assess the shape of these aircraft as early in the design process as possible allows a greater understanding of the air vehicle drivers and the design compromises that must be made.

CAD is used in the definition of the relationship between the external surfaces and the internal packages. For example the creation of the CATIA model described in 2.1.4 permitted a better understanding of the effect of the clearance on passenger height, the potential availability of exits, and the space required for access to those exits. As with the external shape, parameterised geometry defining the packaged items can be implemented in CATIA, and these can be 'morphed' between configurations.

Another example of the use of CAD in packaging was during the concept definition phase of a loitering munition, Fig 14. In this example, the maximum envelope of the outer surface was defined by operational needs, and it was necessary to determine the volume and mass available for fuel and payload. By using

CATIA a range of cross sections and longitudinal sections were quickly assessed to determine the most suitable shape, whilst meeting the payload and volume requirements. A better understanding of the mass and balance characteristics of the vehicle was obtained by applying the appropriate material characteristics.

Within the process defined in Fig 1, a common CAD model can be shared with the aerodynamics and structures disciplines. This allows the generation of response surfaces suitable for use in a synthesis program developed for this type of vehicle. Once the DSO code has been created the design process can be completed by using the CATIA model to check the volume calculations, and the implementation of the complex geometric rules.

4 Performance analysis

In parallel with the work on generalising the geometric description of air vehicles, the performance analysis methods employed are being reviewed, and extended or replaced where necessary. 'Performance' in this context includes not only aerodynamics, propulsion characteristics, vehicle mass, and mission performance, but also vehicle controllability, cost and observability.

The analysis methods used within existing syntheses [10], [3] are often not applicable to novel concepts. There is a need for more data to extend the coverage of the design space and this is being generated by a combination of analytic studies and experimental measurements as described in Ref 7. Thus for the UCAV application described in 2.2.2 above, the current aerodynamic and structural mass analyses are based on an equivalent trapezoidal wing. This approach may lead to significant errors for some wing planforms, so response surfaces are being generated to capture the effects of the cranked wing geometry on the wing mass and aerodynamic performance.

New analysis methods are now being defined by the relevant specialists in areas, such as controllability and observability, where past design syntheses relied on simple, approximate rules.

It will be impossible to generate response surface models to cover all possible concepts that can be generated by the parameterised geometry modelling. Therefore modules applicable to a more restricted range of shapes will be created for particular classes of air vehicle.

5 Optimisation

The current DSO programs have very few common elements apart from the QinetiQ numerical optimisation routine RQPMIN (Recursive Quadratic Program for Minima) [11]. Evaluation of alternative optimisation strategies (e.g. genetic algorithms to determine global optima) has confirmed the superiority of gradient-based methods for air vehicle design problems. Because of the large number of constraints inherent in this type of problem the optimum design lies, in general, on the intersection of several constraint boundaries. While gradient methods can potentially produce local optima it has been found that they allow the user to understand quickly the sensitivity of the design space to the design constraints and thus obtain an optimum solution. Development at QinetiQ therefore continues to be focused on RQPMIN.

6 Concept applications

DSO has recently been applied to the conceptual design of a missile. The development programme is providing a demonstration of the viability of this approach. The current program models a simple missile body with a tangent-ogive nose section, cylindrical body and tapered or flared aft section. Up to two sets of four fins may be included, actuated or fixed, aligned or interdigitated. Rules for the packaging of the contents of the missile (warhead, electronics, fin actuators) have been incorporated, with constraints to ensure that the components do not overlap and are enclosed within the missile body. The model assumes a rocket motor, consisting of one or two stages, each of which may be end- or radial-burning. Aerodynamic performance is obtained from Missile DATCOM [12].

Fig 15 shows the datum missile configuration which has been sized to meet a given range requirement. It has two sets of aligned fins, and is geometrically similar to Sparrow / Skyflash missile. The fins are of fixed geometry, the diameter of the missile is fixed but the missile length is allowed to vary. The rocket motor is a neutral radial burner i.e. no change of burn area with time. A very simple trajectory is assumed in which the missile flies straight and level from launch until the propellant is exhausted, and then continues on a ballistic flight path until it reaches the ground. The effects of aerodynamic drag during the ballistic phase have not been taken into account. The optimiser ensures the satisfactory packaging of the internal items (no spare volume) and chooses the length of propellant chamber to give the thrust and burn time necessary to achieve the required range.

Fig 16 shows the effect on missile mass of altering the range requirement. The launch mass reflects both the change in missile length to house the necessary propellant chamber, and the change in propellant mass. In general terms doubling the required range increases the missile launch mass by 30%.

Fig 16 also shows the flight profiles for the five ranges considered. It is interesting to note that the missile required to fly furthest has the shortest duration of powered flight. This illustrates the trade-off between burn time and thrust for a radial burner of fixed nozzle dimensions. To increase range a greater propellant length (and hence a larger burn area) is chosen by the optimiser, giving a shorter burn time but a higher thrust, which results in a greater horizontal speed of the missile at the end of the powered leg.

The estimation of aerodynamic performance by DATCOM at multiple points in the powered leg of the trajectory leads to a relatively long execution time (Table 1). The current time-stepping approach for this leg is being replaced by a more rapid integral method. Further development work is covering more detailed trajectory modelling, enabling a mission to be described as a number of legs with a range of end conditions. In addition non-circular bodies and alternative propulsion systems e.g. gas turbine, liquid fuelled rocket motors and ramjets are likely to be considered.

6 Concluding remarks

Building on extensive experience with design synthesis methods for air vehicles, QinetiQ has instigated a series of major developments. The encouraging results from this work show the potential for synthesising a wide diversity of air vehicle shapes. Work has begun at QinetiQ on implementing an entirely modular DSO method. The new method, Air vehicle Preliminary Design Optimisation, (APREDO), will incorporate the elements described above. This approach will permit the rapid generation of syntheses tailored to particular types of concept.

The improved coverage and power of the new design synthesis methods are making an important contribution to the generic process for design optimisation being developed at QinetiQ.

CAD, though not built into the design synthesis, forms an indispensable part of the process of defining vehicle geometry and packaging, and facilitating the rapid analyses by technology specialists that support the concept design. In the longer term further increases in computer performance per unit cost may result in CAD tools assuming an even more central role. For the foreseeable future there is likely to be a need for both broad DSO studies, with approximate models giving results in minutes, and in-depth, multi-disciplinary studies requiring a timescale of days.

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Optimisation case	Number of variables	Total number of constraints	Number of function calls	Execution time (sec)
1. Cross sections	10	4	99	<1
2. Centre-line section	14	8	323	<2
3. General body	20	18	1121	4
4. BWB packaging	46	35	2400	~150
5. Cranked wing UAV	61	89	14000	~100
6. Simple missile	61	60	1800	420

Table 1 Example cases of design synthesis and optimisation

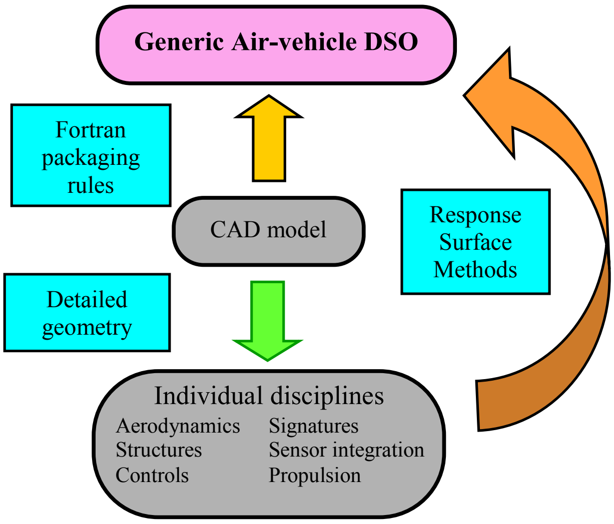

Fig 1. Generic process for design optimisation

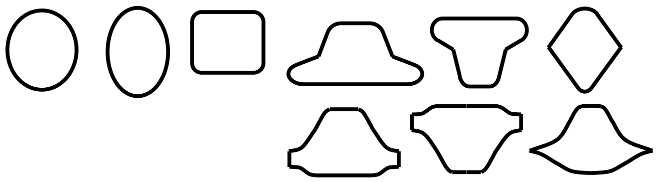

Fig 2.Typical discrete and blended body cross sections

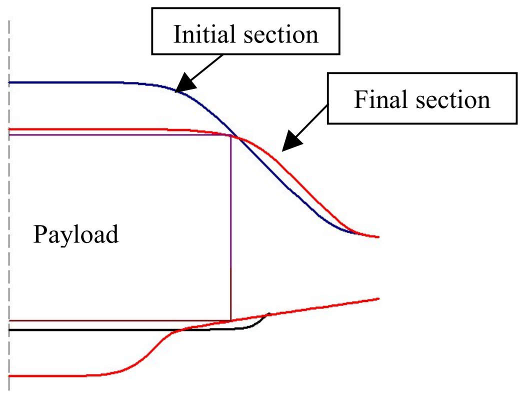

Fig 3. Forward of 2 body cross sections optimised to enclose payload bay

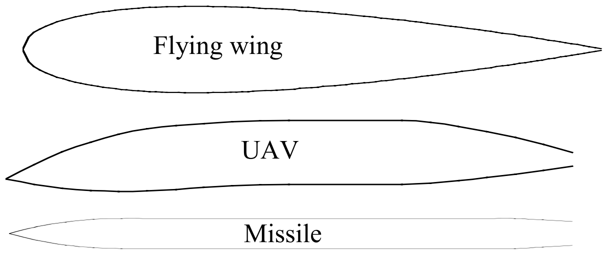

Fig 4 Typical body centre-line sections

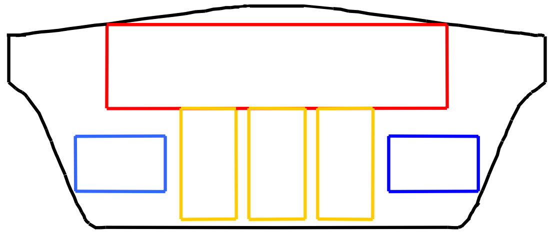

Fig 9. Cross section through optimised BWB section wrapped around the internal packages.

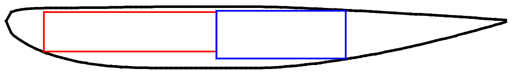

Fig 5 Centre-line section of flying wing optimised to contain 2 internal items

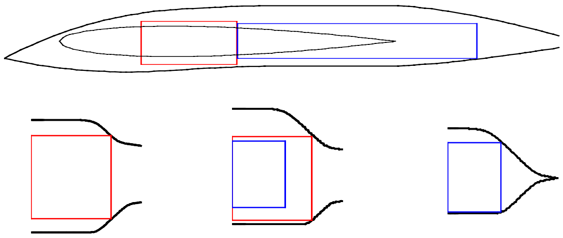

Fig 6 Body of UAV optimised to contain 2 internal items

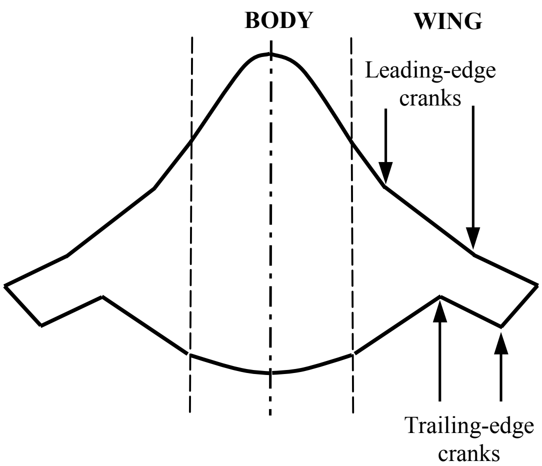

Fig 10 plan view of air vehicle

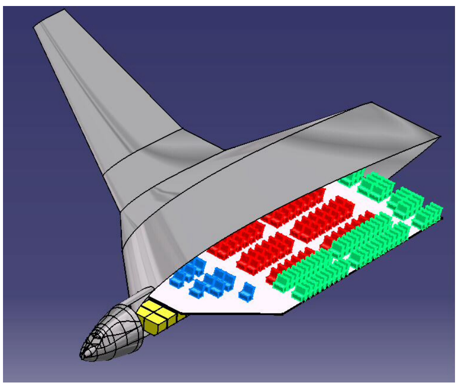

Fig 7 Modelling of BWB aircraft

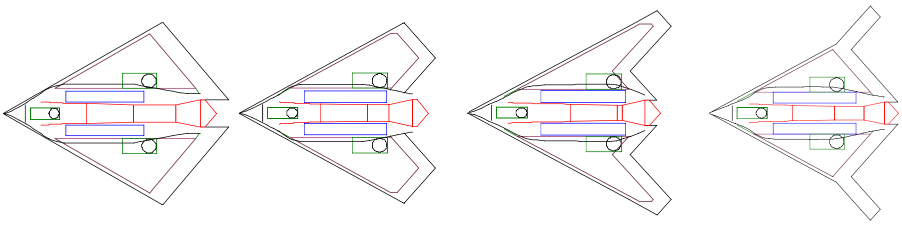

Fig 11 UCAV wing planforms with the progressive addition of leading- and trailing-edge cranks

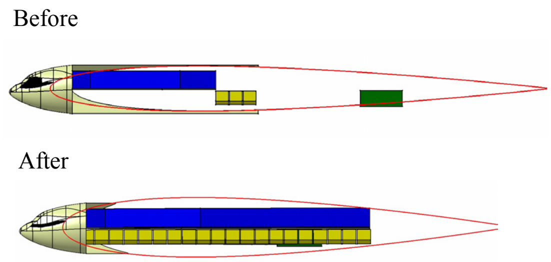

Fig 8 Cross section of a blended-wing-body aircraft before and after optimisation

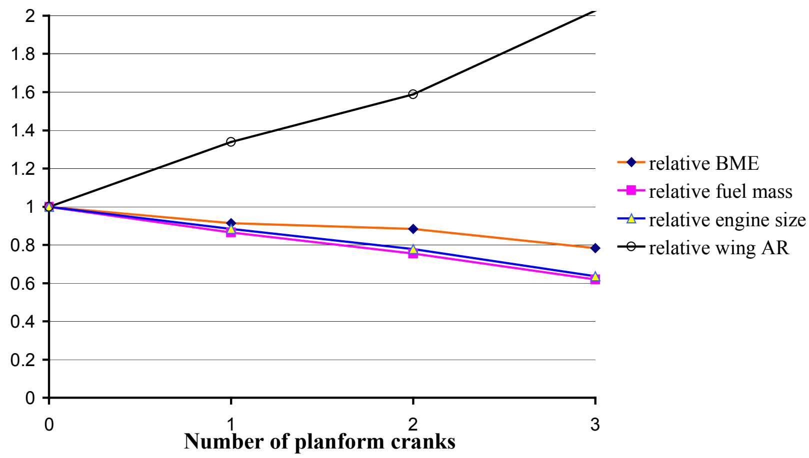

Fig 12 Effect of number of wing planform cranks on UCAV characteristics

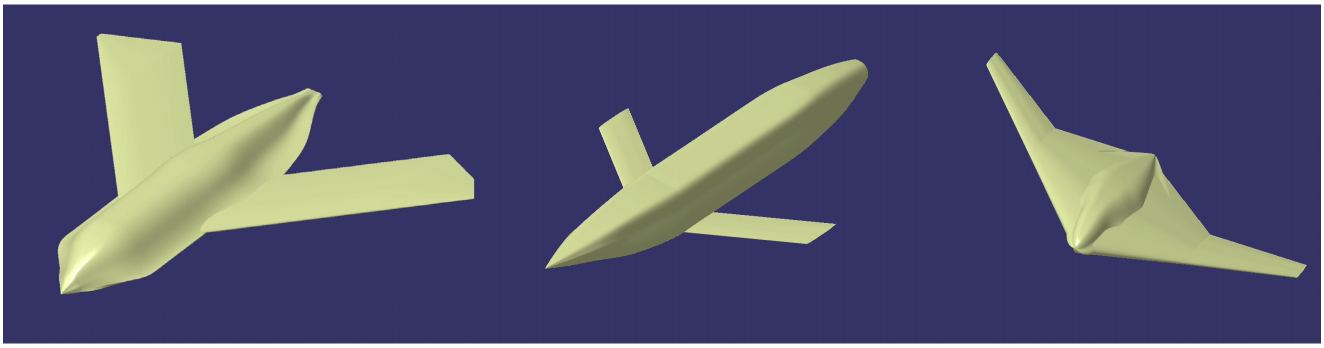

Fig 13 Wing-body combinations generated by generic geometry parameterisation

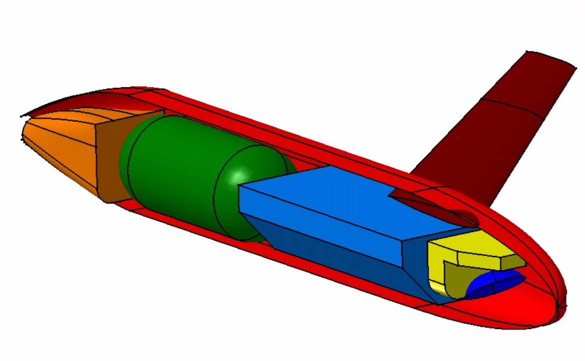

Fig 14 Internal packaging of a loitering munition defined by CATIA

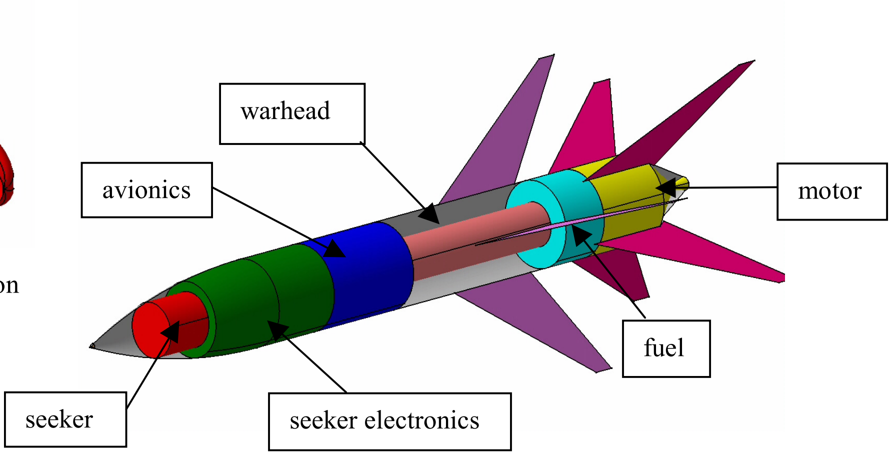

Fig 15. Simplified packaging of a missile

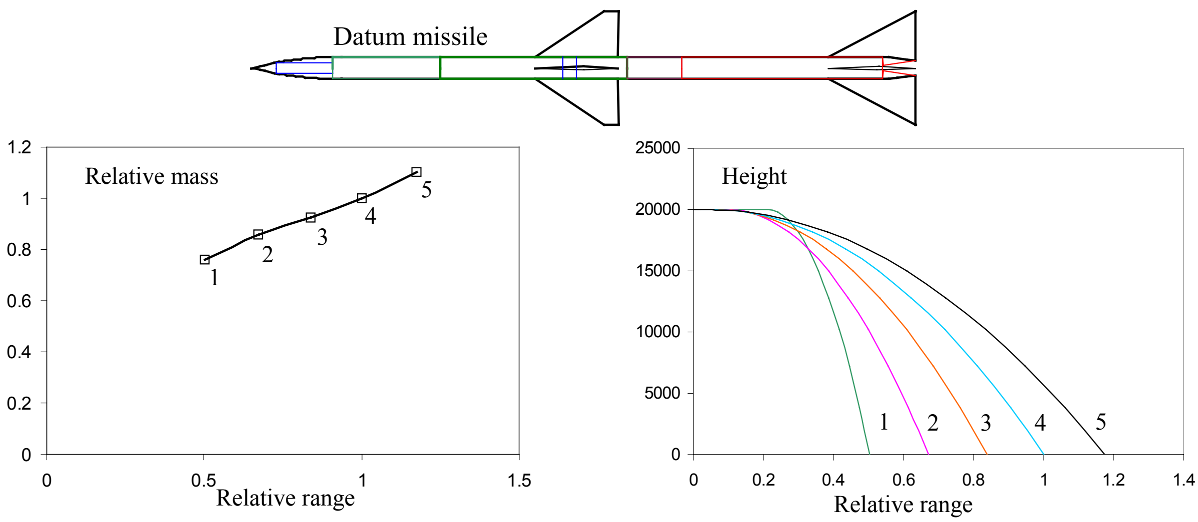

Fig 16. Missile design synthesis - effect of range requirement on vehicle mass