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DISTRIBUTED ARTIFICIAL INTELLIGENCE APPLIED TO DESIGN OF AIRCRAFT FUSELAGE AND WINGS

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Summary

Aircraft design process is complex, requiring a wide spectrum of expertise of many engineers from different disciplines involving a combination of experience and judgement. Moreover, aircraft design involves a series of components descriptions at various levels of detail with an iterative design process modified towards a superior product to its predecessors. Today computer assisted design exists in all forms from computational analysis for capturing the 'know-how' by using artificial intelligence techniques.

This paper focuses on the development of a multi-agent knowledge-based systems to design aircraft fuselage and wing components at the preliminary stage in a distributed design environment. In addition, prototype development discussions are presented on how distributed artificial intelligence techniques can be used to coordinate behaviour among a collection of semi-autonomous problem-solving agents: how they can coordinate to act together, solve joint problems or make individually or globally reasonable decisions despite uncertainty and conflict.

Introduction

Aircraft design involves a series of component descriptions at various levels of detail with an iterative design process modified towards a superior product to its predecessors. This cyclic process synthesising sequence of operations, starting from the specifications analysed by the designer often involves the use of computer-aided design (CAD) systems, then evaluated and amended. The more iterations that can be performed within the constraints of time and money, the better the results. Not only is the aircraft design process complex, but it also requires the expertise of many engineers from different disciplines, and it is also true for the preliminary design stage.

Traditional computing techniques have been used in the aerospace industry for a number of years and have been directed at either numerical analysis or data processing with limitations in assisting designers. Many attempts have been made towards the development of computer assisted aircraft design tools [1,11] which aim at encapsulating the knowledge of an experienced designer into an "intelligent" computer program. These programs have been directed at simulating the process of human reasoning using computer techniques such as artificial intelligence (AI).

Besides such technological advances, modern aircraft design activities are becoming an international collaboration affair where different parts of the aircraft are designed in different countries. Using sophisticated computer techniques and broadband communication networks will allow information to be sent down these lines. To be able to take advantage of such technology in the aerospace industry requires the revolution of current computer systems to cope with this change. The use of distributed artificial intelligence (DAI) allows to address such issues and have control over this distributed design process. DAI provides a methodology to coordinate behaviour among a collection of semi-autonomous problem-solving agents: how they can coordinate to act together, solve joint problems, or to make individually or globally reasonable decisions despite uncertainty and conflict.

This paper focuses on trying to capture the knowledge of both fuselage and wing design by building a prototype knowledge-based system (KBS) (branch of AI technique) agents which are autonomously intelligent, but can also communicate with one another. For example, the aircraft fuselage agent is not only capable of designing its main components (eg seat positioning, length, width), but also make sure that the correct information or calculation is passed on to the wing design agent (eg wing torque box, whether it is a high wing or low wing fuselage attachment and fuel piping). The paper goes on to describe what aircraft knowledge was used and how it was represented in a AI tool system.

Two students initially worked independently to gain the domain knowledge: fuselage and wing, which was then brought together to build the distributed knowledge based systems to perform a distributed aircraft design.

Artificial Intelligence

The term "Artificial Intelligence" (AI) was first introduced at the 1956 Dartmouth College, USA Conference organised by Minsky and McCarthy. Initially, AI research efforts were much concerned with attempts to produce programs which simulated the way in which a human displayed 'intelligent behaviour' Winstanley identifies four elements that intelligent behaviour can be considered to comprise [14]: Reasoned behaviour, organised and dynamic memory, effective communication skills and the ability to learn.

AI encompasses many diverse specialist fields: Natural language, pattern recognition (vision), machine learning, robotics and knowledge-based systems. The type of AI technique used for the design of aircraft fuselage and wing study was Knowledge-Based Systems (KBS).

Knowledge-Based Systems (KBS)

KBS differs from conventional programs in that: Conventional programs use algorithms and numeric processing to solve problems [10]. In other words, the program control functions and the "knowledge" components of a conventional program are both contained, interwoven, in the program algorithm.

eg. Algorithm = Logic & Control

On the other hand KBS programs are organised differently in that, the program control functions and the problem "knowledge" components are separated in the KBS programs. Unlike conventional programs, which are confined to numeric representation of data, KBS represents knowledge and solve problems using heuristic (rules-of-thumb) methods expressed as:

eg. Heuristic = Activity + Pragmatic Soln.

This defines that a heuristic method contains the need which is to be satisfied and a solution method that has, in the past, proven to satisfy the need. Unlike an algorithmic solution, a heuristic solution may not always return a unique solution. Moreover, KBS' are able to use symbolic representation of data and symbolic processing.

KBS are used in situations/problems for which no exact algorithm solutions are known and those problems for which algorithmic solutions are computationally not feasible. Aircraft design presents both the use of algorithmic as well as heuristic processing of data/information. In our study the KBS chosen managed to incorporate both these aspects and with more emphasis placed on the heuristic manipulation (explained later). Furthermore, KBS solution for a problem for which there is a practical algorithmic solution may result in an inefficient and computationally expensive program, in terms of cost and processing power. Thus, in many cases hybrid systems (KBS and conventional programs) can be used to alleviate this scenario.

KBS technology was used, together with the approach of distributed design.

Before the details of the prototype system are discussed, a brief outline of distributed artificial intelligence is presented:

Distributed Artificial Intelligence

Distributed Artificial Intelligence (DAI) suggests a synthesis of distributed computing and artificial intelligence. In fact it has two sides, theoretical and practical. The theoretical sides enable problems to be structured in an elegant framework other than a sequential one, placing an important role in many problem-solving strategies simultaneously. The practical structure limits it to the amount of information that can be brought together for solving problems.

DAI distributes the software architecture as well as the computing resources. Each node in this distributed network is a self-contained reasoning entity. Many of the DAI projects in engineering involve distributed intelligent agent (DIA) and explore the interaction of several nodes, each of which is intelligent. (An agent is an intelligent System). Generally speaking DIA includes scenarios in which a person interacts with an AI program, as well as scenarios in which multiple AI programs interact [6]. Much of the original impetus for DAI came by way of DIA [5] (e.g. HEARSAY - II speech project based on several expert knowledge sources communicating collectively).

Aircraft manufacturers and designers are geographically distributed and coordination on any new aircraft design project involves a considerable amount of effort in terms of both travel and negotiations of designs. Moreover, the lead time becomes very important if one is to compete effectively in this highly competitive aircraft market. Thus, DAI can allow the coordination of these geographically separated design activities without incurring travel costs, cost of international meetings and without overloading the communication network that they can share [3].

The system Architecture

The KBS chosen for the prototype development and study was Crystal developed by the two students working as knowledge engineers. Crystal is an expert system shell which consists of the following components (Figure 1):

- i) knowledge base
- ii) inference engine
- iii) user interface

i) Knowledge Base

This consists of the domain specific rules (in this case aircraft wing and fuselage design) and facts which have been identified and coded. The order of rules which are considered as important and thus structuring them within the knowledge base requires the use of formalised methods.

ii) Inference Engine

This is part of the KBS which processes the knowledge stored within the knowledge base and links to the user interface. The key difference between conventional programs here is that the KBS separates its knowledge components from the program. The Crystal, expert system shell, provides an inference engine and a general knowledge organisation framework for the inference engine.

The inference engine uses an iterative process of examining rules or facts from the knowledge base, as well as forming intermediate conclusions based on the rules executed thus far. More rules are reviewed, dependent upon the intermediate conclusions, until a final solution is reached.

Several different types of interfacing strategies are available for processing rules and facts from the knowledge base using Crystal.

a) *Forward chaining* - a search strategy which attempts to find a solution from a given set of data.

b) *Backward chaining* - starts with a goal, and then attempts to prove the goal by determining the conditions required to attain the goal, or end point.

Backward chaining systems ask questions as the KBS deems necessary whilst trying to prove a goal. Forward chaining systems tend to ask all questions first and then attempts to find a solution.

c) *Search Strategies* - For example, breath-first search examines all possible alternatives at a particular rule level before examining relevant rules at the next lowest rule level.

Choosing the search strategy depends on the problem at hand and the one chosen for the prototype was backward chaining and breadth-first search. It is important to realise that the organisation of the knowledge base depends on the search strategy used by the inference engine.

It is worth pointing out at this stage that AI languages (symbolic computer) such as C/C++, Prolog, Lisp and Smalltalk were considered, but due to a quick implementation run, an expert system shell was chosen. These languages provide little system structure, but a great deal of flexibility in the way a KBS can be controlled and the knowledge can be represented.

Crystal's ease of use and its interface with C programs allowed the system to enable to have hybrid facilities to tackle both the symbolic and algorithmic data manipulation. Moreover, Crystal's portability, the fact that it ran under DOS linking to spreadsheets and databases and the graphics toolkit capabilities provided aircraft data to be represented graphically.

iii) Crystal's User Interface

The Crystal toolkit caters for customising user interfaces by using its integral menu options or through external C language routines.

Type of Aircraft Design Knowledge

This comes from a variety of sources such as specification, requirements, air-worthiness, aeronautical engineering rules, design characteristics of each component,design process, experience and flair.

Some of this codified and fixed (i.e. specification and requirements), broken down into subproblems (i.e. performance broken down into landing, take-off, and cruise performance) and established in a database (i.e. incorporation of the state-of-the-art technology), imaginative (i.e. unconventional configuration), subjective (i.e. designer's flair in favour of low wing position) and predictable (i.e. design trend in the use of composite or smart materials).

Aircraft design knowledge can be classified into the following types:

Governing Knowledge:

Obtained from airworthiness requirements and mathematical formulations with respect to aerodynamics, structural analysis, etc.

Configuration Knowledge:

Relates the aircraft to its diversified configurations and relates configuration components to their type, number and position for integration.

Supportable Knowledge:

To obtain the knowledge needed for designer's judgement, resource can be made to establish data through retrieval, results from a program execution and predictable design trends. Otherwise, the designer can depend upon his experience, common sense or sometimes flair. This knowledge is simple and acquired without undue difficulty. However, subjective characteristics come from experience and flair.

Metalevel Knowledge

Means knowledge about knowledge. Once factual design knowledge and its logical connections are represented, the methods to use and control such knowledge are needed to search for the solution. It is used to set priorities or order of preferences and guide the search process and control the knowledge to be added to or excluded from the knowledge base by using heuristics or rules, effectively limiting the search for a solution.

Domain Knowledge

The domain knowledge chosen for the prototype study was based on preliminary aircraft fuselage and wing design. An initial specification knowledge base was coded which captured the aircraft performance objectives. Cruising mach number, cruising altitude, etc. Then the development of two separate knowledge bases was conducted by two research students: fuselage and wing knowledge bases.

Fuselage Knowledge Base Development

The fuselage design was focused on the passenger transport and restricted to the cross-sectional circular shape based on two circle segments.

The general aircraft arrangement is tied up with the fuselage configuration as well as the initial specification. Its fuselage needs to be optimally designed to cater for the revenue earning capability, in terms of passengers, as well as house the cockpit, galley and sometimes the retractable undercarriage and/or fuel.

The fuselage design knowledge base was developed by elicitating knowledge through literature [3, 4, 9, 12] and through local experts at Cranfield University, College of Aeronautics.

Various constraints and associated rules (and facts) were identified such as: the drag on the fuselage, should possess rigidity and ease for inspection, as well as number of passengers. In addition, the design process contained rules of optimising the number of possible seats with different arrangements within the fuselage (Figure 6), cross-sectional design using empirical data and rules, details of the doors and windows including emergency exits as well as space for the wing centre section, attachment frames of engines and retraction for the landing gear. Appropriate distances were also accommodated for standard or custom cargo compartments below the passenger deck.

The fuselage preliminary design process follows a procedure step but with many feedback loops allowing to optimise on the various constraints put into the model. Figure 2 depicts this process and Figure 3 shows the associated fuselage knowledge base modules making up the fuselage design process. These modules are:

Fu-spec.kb	(fuselage specification)
Fu-length.kb	(fuselage length)
Fu-floor.kb	(fuselage floor)
Fu-cargo.kb	(fuselage cargo bay)
Fu-box.kb	(fuselage/wing torque box)

Wing Knowledge Base Development

Having defined the basic role of the aircraft the wing design is initiated by calculating the performance characteristics (design specifications and operational cost). However, flight characteristics need to be satisfied at various speeds and altitudes with various configurations (flap angles and power settings), design and structure within the general arrangement (satisfying strength, rigidity, weight, accessibility, etc) and sufficient space to accommodate the required fuel and undercarriage retraction. The type of engines will also be chosen at this stage.

Various calculations are conducted by using rules for wing design and knowledge acquired from local experts and literature. These rules and calculations are: wing arrangement decided by: wing taper ratio - and which airfoil to use etc.

Figure 4 depicts the knowledge base modules used in the wing design which are:

Weight,kb	(Wing weight estimation)
Param.kb	(Wing parametric design)
Wing.kb	(Wing configuration)

Again, like the fuselage controller knowledge base, the wing knowledge bases are controlled by the W.control.kb module allowing for the control of the flow of wing design.

The Neutral Knowledge Base

This knowledge base module contains sub modules for the specification of the aircraft as well as knowledge to create geometrical image (graphics) of the fuselage and wing configuration. Figure 5 depicts this Neutral knowledge base which is used to cater for the two; wing and fuselage knowledge-based (expert) systems acting as intelligent agents to communicate with one another. Moreover, the Neutral knowledge base system forms part of an expert system providing metalevel knowledge to control the flow of knowledge, the design process and the search for a solution using heuristics and rules.

Development of Fuselage and Wing Distributed Knowledge Based Systems

The knowledge elicitation process involved elicitating information from local experts as well as current literature [7]. Moreover, having elicitated the information, a lengthy task of structuring the knowledge was involved. However, the predefined structure of Crystal knowledge representation scheme "Rules" enabled this to be achieved effectively. At this stage the two designers were working independently as knowledge engineers to acquire knowledge, one for the fuselage design and the other for the wing design.

Fuselage Knowledge Based System

The KBS developed for civil fuselage design using various preliminary design procedures. These were:

- Cross sectional selection
- Accommodation of freight, passengers,
- Passenger cabin requirements

- Cabin length and diameter calculation.
- Floor height positioning.
- Container choice including its dimensions.
- Wing box cross section.

Initially, the basic shape of the fuselage is designed based on the input requirements and the number of passengers it is required to accommodate. An iterative process is then involved in attempting to classify first, business and economy class passengers and vary the seating arrangement accordingly (Figure 2). The cross-sectional shape is constructed which depends on the number of seats abreast the designer has chosen. Optimising the fuselage for the highest density class usually ensures the best use of space and therefore a more profitable configuration for the company.

The overall length of the fuselage is determined by taking account of seat spacing (first, business and economy), galley, exits (FAR requirements), toilets and flight deck. Empirical data is used to calculate the tail and nose lengths. Various tests are then conducted [13] such as aerodynamic ratios, bending moments, etc... and relevant adjustments made to the fuselage arrangement.

The floor height is calculated so that it is within an acceptable range and provides a guideline for cargo capacity. The cargo bay volume is calculated so that the best fit standard containers can be used (a list obtained from a database). However, the knowledge-based system also caters for a customised container. This is performed graphically so that the designer can visualise his/her choice of the container situated in the cargo bay. Again an interactive and iterative process is performed aided by the knowledge based system as well as tests against requirements and constraints.

The wing box cross section is calculated by gaining data through the wing knowledge based system design. Moreover, various constraints such as the undesirability of interrupting the cabin by a wing torque box, maintaining the same floor and ceiling height throughout the cabin. At this stage revisit of previous calculations of floor height and diameter are possible if a non conventional torque box arrangement is chosen.

Wing Knowledge Based System

The wing knowledge based system carries out the wing height estimation, performance estimation and the selection of wing planforms and the airfoil. The weight estimation evaluates payload based on passengers, baggage and cargo from the input requirements and mission specifications. The gross take-off weight is based on empirical data (in this case using data from existing aircrafts). Mission fuel weight and empty weight are also calculated.

Performance characteristics are determined to calculate the wing loading and thrust loading. The landing performance and configuration is also estimated based on the known take-off wing loading, the take-off weight and mission fuel weight. Various validation processes are conducted through the wing KBS and appropriate modifications made to the performance characteristics. *Param.kb* knowledge base is used to conduct these calculations.

Wing planform is constructed and dimensioned from the previous data generated as well as further inputs requested by the system from the designer. Moreover, the designer is asked to select an airfoil from a list in a database for a particular aeroplane characteristic. The *Wing.kb* knowledge base is used to hold this design knowledge.

The Distributed Design Process

Based on the distributed design system architecture depicted in Figure 7, the modular knowledge bases proved to be a useful arrangement so that various information and results can be used to facilitate other operations from modules outside their current knowledge based system environment. For example, the fuselage box knowledge base Fu-box.kb can request information from the Wing.kb knowledge base which resides in the Wing KBS. In fact both the Wing and Fuselage KBS here act as intelligent agents which are able to conduct wing and fuselage design and pass relevant information on to each other.

The advantage of the modular approach allows the programmes to be flexible in their design as well as accommodating the ease of maintenance and future enhancements to these knowledge-base modules.

Communication between the KBS

The communication links shown by Figure 7 suggest that communication is first established through the overall controller module, called Neutral.kb, and then with either fuselage (FControl.kb) or wing (WControl.kb) and then through its sub-components. A Control.kb keeps track of current data that have previously been generated by either wing or fuselage designs. The Update.kb records any change as a result of operating either the fuselage or Wing KBS. However, at all times the controller modules act as the main interface modules which help perform distributed design with relative ease.

The communication between the various control modules and the sub modules (knowledge bases) is performed by what we have termed a mail system. Thus, each time a particular knowledge base is opened it will examine its mail box to see if there is any updated information placed within it as a result of calculations conducted by other modules. Moreover, once the particular knowledge base has been used within the KBS and new information have emerged they will then be sent to the appropriate modules to which this data is useful or mandatory as well as trigger a flag to state that there has been an update of the design process. This updated information will be recorded onto the Update.kb as depicted in Figure 7.

It can be seen that three KBS have been created, Fuselage, Wing and Neutral and each of these acting as distributed agents which can communicate the essential data to one another. Moreover, the Update.kb and Control.kb modules provide a buffer to pass the information to the right modules cohesively.

Discussion and Conclusions

The implement knowledge-based system (KBS) architecture in a modular fashion allowed a distributed design process of preliminary aircraft fuselage and wing design to be performed. Although, the process represented is fairly simplistic to implement, it illustrates the flexibility of such a concept and the usefulness for future aircraft designs across international boundaries with a number of design teams working concurrently. It must be noted that the security issue of data protection has not been addressed by this project.

The prototype was tested and successfully demonstrated and met the objectives set out, but improvements for further work have been identified:

- Increase the number of active agents e.g. undercarriage, tail, etc., so that a preliminary aircraft can be designed using distributed AI techniques.
- Incorporate more detailed calculations such as aerodynamic and structural.
- Incorporate manufacturability for the next stage after preliminary design.

Crystal has proved to be an effective tool for developing KBS, but lacked the availability of a range of knowledge representation schemes. Although the graphics capabilities of Crystal were exploited, it also lacked computer aided design (CAD) graphics, which would have been advantageous in detailing the aircraft geometry.

Finally, the modular approach suggests that the use of an object-oriented KBS would prove to be more advantageous, offering all the facilities of flexible computer program design, for example, C++ language.

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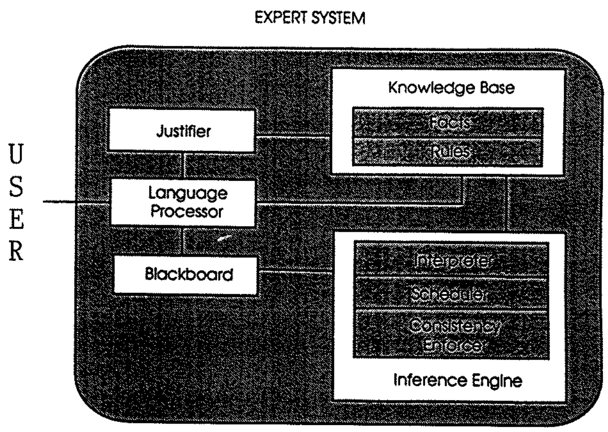


Figure 1 Expert System Components

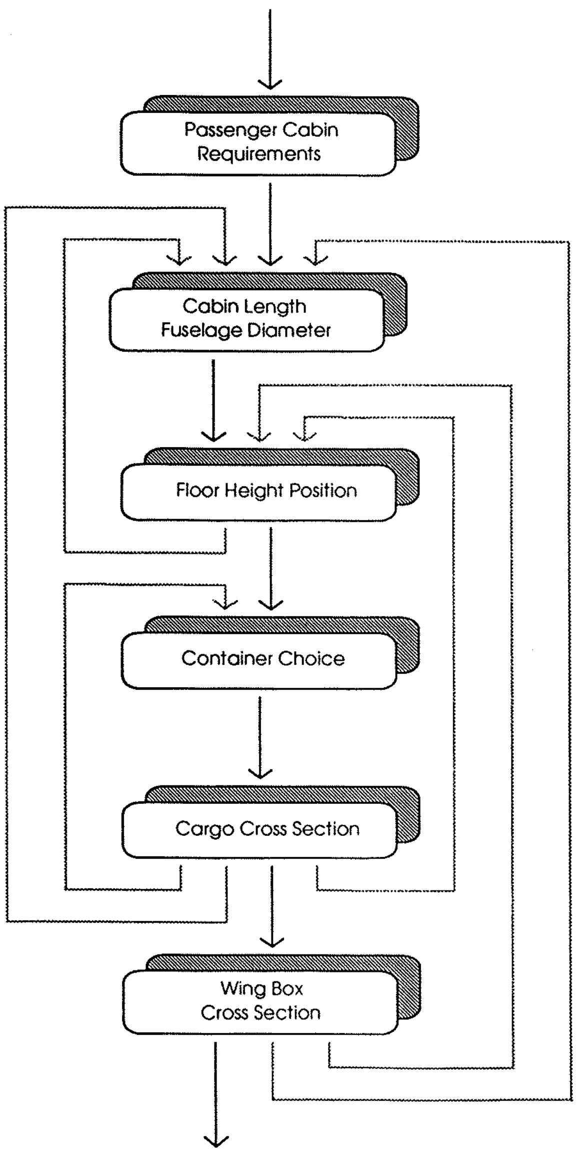


Figure 2. Fuselage Preliminary Design Process

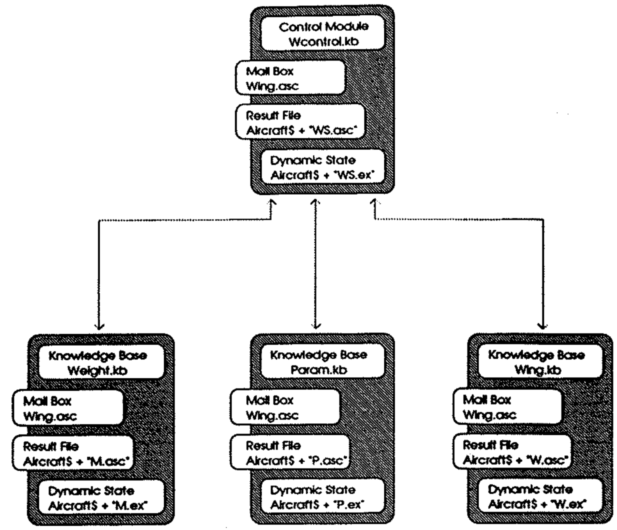


Figure 4 Wing Preliminary Design KBS Architecture

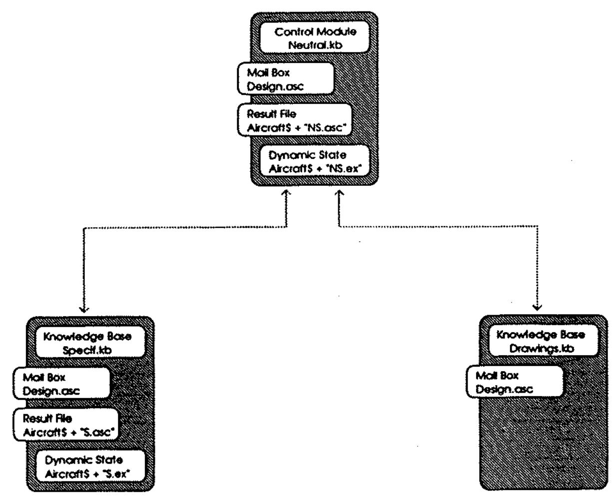


Figure 5 Neutral (Controller) Module Architecture

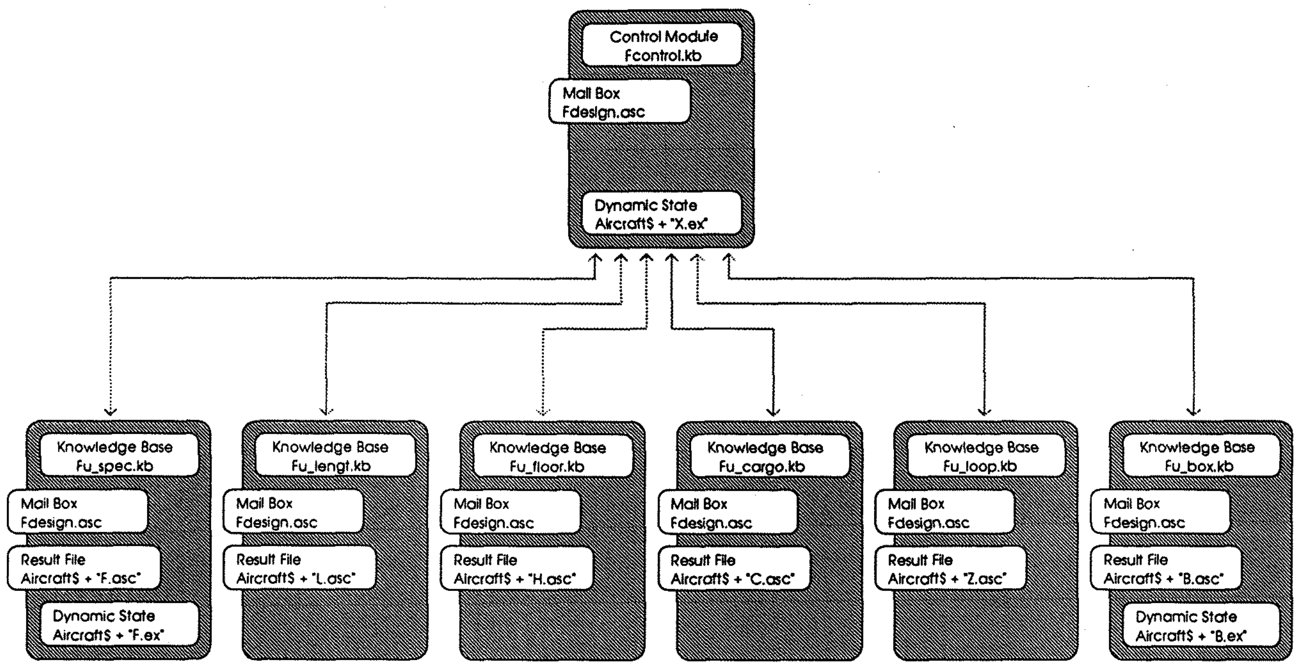
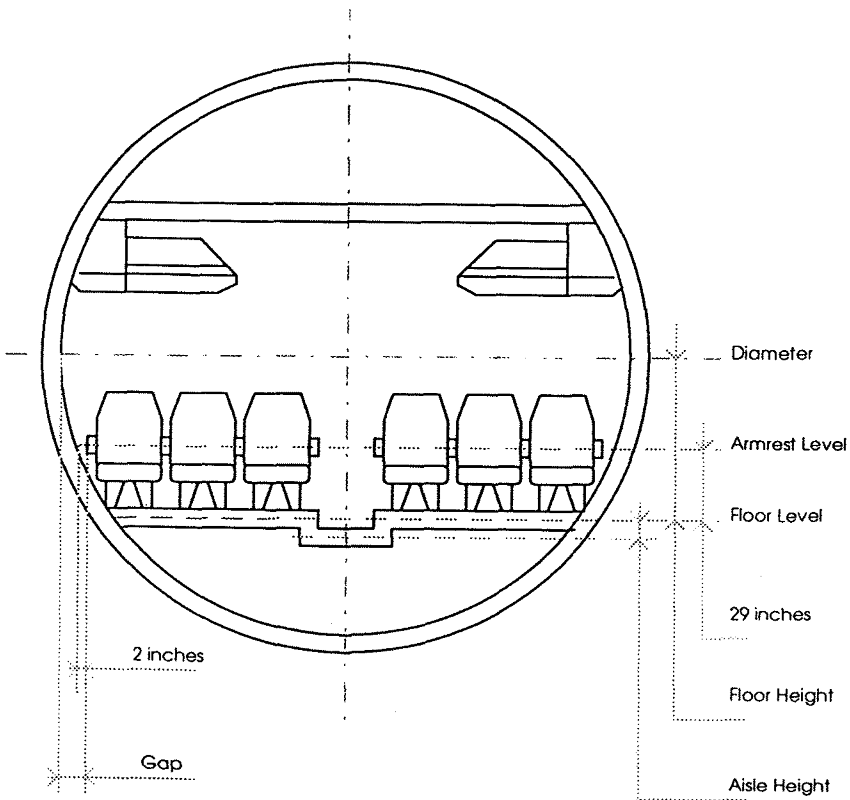


Figure 3. Fuselage Preliminary Design KBS Architecture



$$Gap = 2 + Diameter/2 - sqrt(Diameter^2 / 4 - (Floor\ Height - 29)^2)$$

Figure 6. Cabin Requirements and Cargo Bay Design

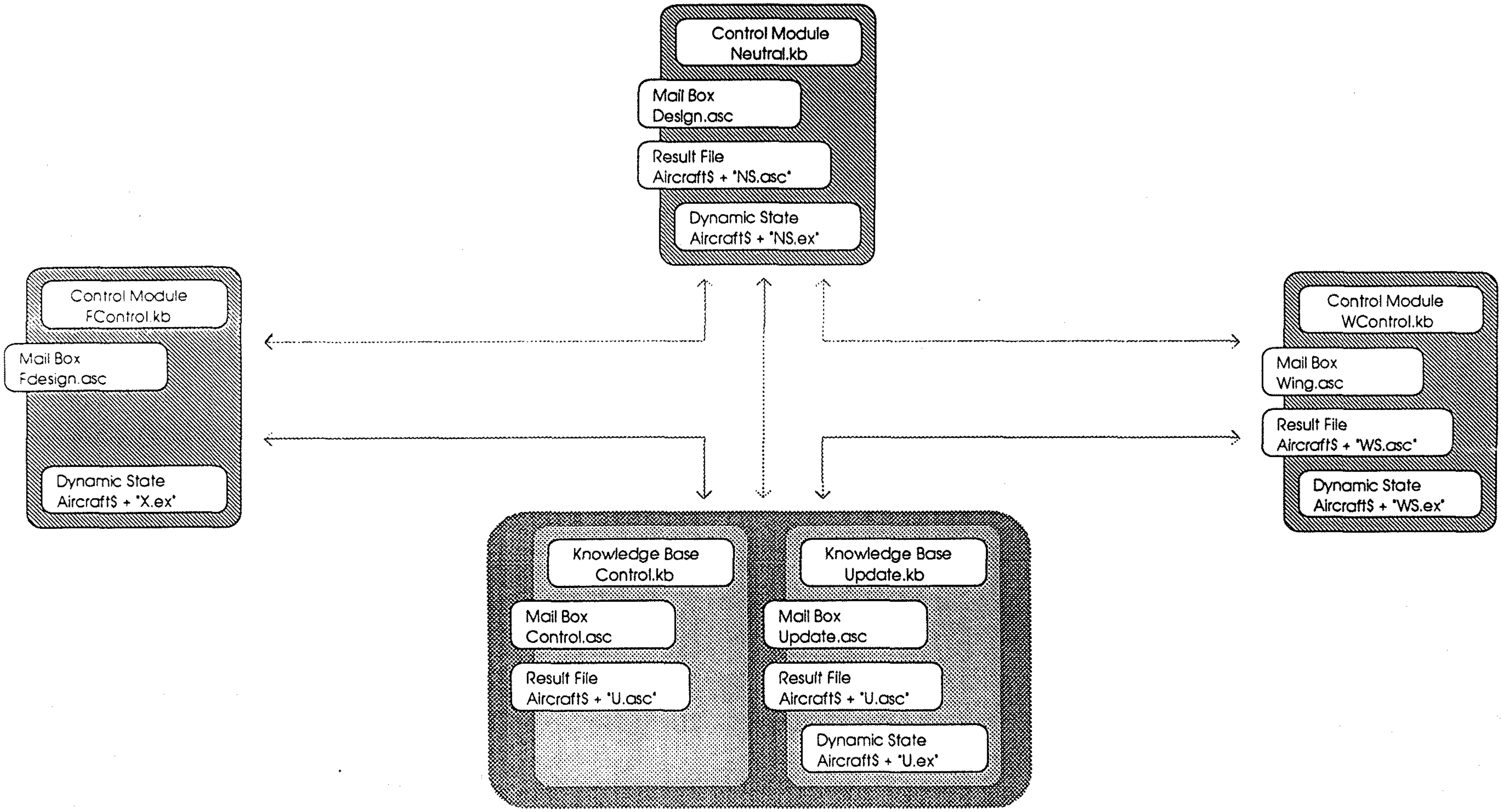


Figure 7. Overall Distributed Design - System Architecture