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Automated Scheme Adjustment for Conceptual Aircraft Design and Optimization

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Conceptual design is the first phase of developing a new aircraft, in which initial concepts must be generated, analyzed, evaluated, and optimized—usually in a short period of time. To improve the quality and efficiency of this phase, many studies have been conducted on the application of artificial intelligence to the conceptual design process. These authors feel that it is infeasible to develop an intelligent design system that is capable of automatically fulfilling all tasks in this phase, whereas it will be more realistic and useful to support designers with intelligent assistance in the layout and optimization process. A key aspect of that is in the revision of design components following or during design optimization, wherein previously generated geometry must be stretched, scaled, or morphed to reflect analytical adjustments. Automated scheme adjustment is proposed to organize these components in a connection net and make the connected ones act as a whole when one of them is changed. This paper presents the measures for constructing the connection net and controlling the process of adjustment. Through interactive modification and multidisciplinary optimization to a business jet concept, the effectiveness of automated scheme adjustment is depicted.

Introduction

TO improve the quality and efficiency of conceptual design, which is the first phase of aircraft design,[1] artificial intelligence[2] and relevant disciplines have been applied to the process of concepts' evolution, such as rule and case-based reasoning, intelligent optimization algorithms, and agents.[3–7] However, because of the complexity of conceptual design, it is still infeasible to develop an intelligent design system that is capable of automatically fulfilling all tasks in this phase, whereas it will be more realistic and useful to support designers with intelligent assistance when they use such specific tools for conceptual design as AAA,[8] ACSYNT,[9] and RDS.[10]

With a design system called Synthetic Environment for Aircraft Conceptual Design (SEACD),[11] this research focuses on the application of intelligent support through automated scheme adjustment, the basic idea of which is constructing a connection net among the components involved in a concept. This permits the change of one component to cause the automated adjustment of other connected components according to predefined rules and relations. By this means, the system cannot only reduce repeated work of designers, but also keep the realism of concepts under such conditions as optimization,[5,12,13] where human–machine interaction is inapplicable.

Constructing the Connection Net

Automated scheme adjustment entails two types of connection between two related components: equal linkage and datum/attachment. The former connection goes two ways—any one of the components should be automatically adjusted once the other is changed, whereas the datum/attachment connection is one-way; only the change of the datum component will cause automated adjustment of the attached one.

Equal linkage usually exists between components belonging to the same type. Currently, the equal linkage between two fuselage-like components is chiefly concerned. In the business jet used for later discussion (Fig. 1), connections between fore fuselage, middle fuselage, and aft fuselage are equal linkages. Although the designer does not need to model the fuselage of a specific aircraft as three segments, it can be better to break a component with complex shape down into several adjacent ones and model them separately.

Datum components in datum/attachment connections are typically the major ones in a scheme, such as wing and fuselage that contain others smaller components. In particular, if a component has the parameters that can be used as design variables for optimization, it should act as an datum, so that it can cause automatic adjustment of the attachment to avoid unreasonable interference between them. Comparing with datum components, attached components are much more various. An attached component can belong to fuel tanks, landing gears, and standard components[10] that include engine, missile, seat, and so on. Moreover, fuselage-like components, for example, nacelle, as well as such wing-like components as horizontal tail and pylon can be attached to a datum.

Based on the definitions of equal linkage and datum/attachment, connection unit (CU) is defined to store information of the connections to a component. In addition to the type of connection, a CU contains the type and name of the connected component and the index of it in the components that belong to the same type and even have the same name, so that the connected component corresponding to this CU can be identified. Furthermore, a factor list, denoted as α, is included in a CU to describe parameter relations between two connected components. Because each of the components with equal linkage has a CU to identify the other and the datum component has a CU to identify the attachment, the whole connection net can be constructed.

Figure 2 illustrates the connection net of the example business jet. As shown in this figure, mutual intersection caused by rapid three-dimensional modeling often exists between two components. However, this type of relation will not be discussed in this paper because it is used for estimating geometric data[14] instead of for automated scheme adjustment.

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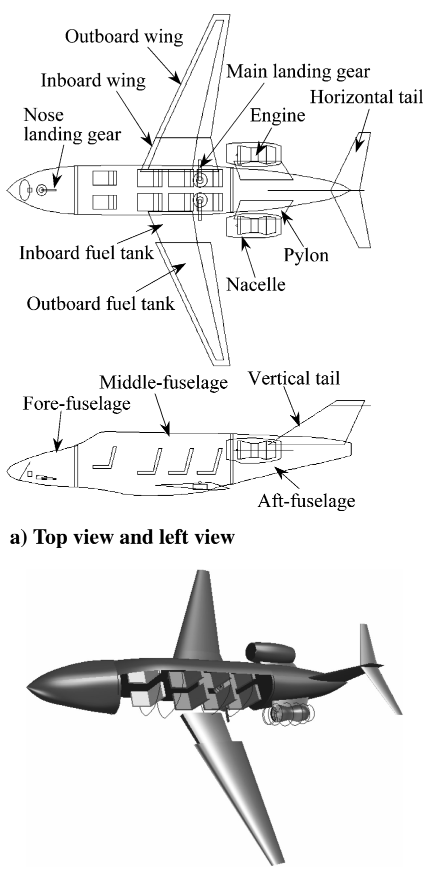
Table 1 Adjustments caused by the change of middle fuselage

Iteration step	Iteration 1	Iteration 2	Iteration 3	Iteration 4
Dominator	Middle fuselage	Fore fuselage	Aft fuselage	——
Items in Candidates	{Middle fuselage}	{Fore fuselage, aft fuselage}	{Aft fuselage}	——
Items in UsedDominators	——	{Middle fuselage}	{Middle fuselage, fore fuselage}	{Middle fuselage, fore fuselage, aft fuselage}
Initialized connections	Fore fuselage/ nose landing gear; aft fuselage/pylon	——	Pylon/nacelle	——
Adjusted components	Fore fuselage; aft fuselage	Nose landing gear	Pylon	——
Adjustments in deeper iterations	——	——	Nacelle/engines	——



a) Top view and left view

b) Three-dimensional surface model

Fig. 1 Components in an example business jet.

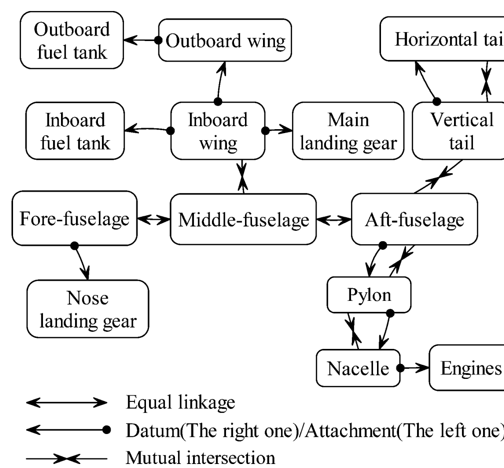


Fig. 2 Connection net of the example aircraft.

General Process of Adjustment

Two basic steps are needed to fulfill automated adjustment. The first step is relating parameters according to predefined rules when a component is to be changed, such as when the designer sends a command through the interface and the optimization algorithm will generate a new design point. That is, all factor lists in the CU list of that component should be initialized with specific methods. However, if the connected component identified in a CU is removed from the scheme after constructing the connection net, this CU should be deleted to update the net.

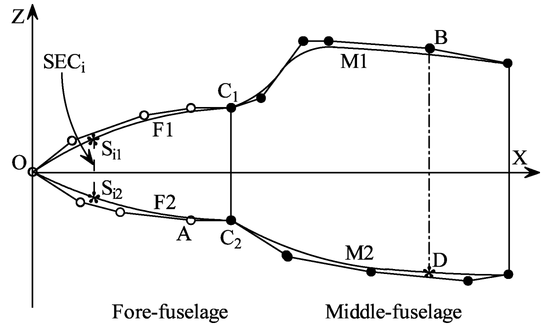
The second step is adjusting connected components based on the parameter relations after the component is changed, and the adjustments will be stopped after all of the items in its CU list have been handled. Because a connected component can have equal linkage with others or function as a datum in another connection, all components identified in the CU list of it should also be automatically adjusted. These subsequential adjustments, called as “deeper iterations,” spread the effect of one component’s change to all relevant nodes in the connection net.

Because the components in an equal linkage are identified with each other, deeper iterations can result in endless iteration of the process. To avoid this condition, the components in equal linkages are dynamically identified in two lists called “Candidates” and “UsedDominators.” The first item of Candidates is denoted as Dominator and cause adjustment of other connected components. However, if a connected one is also identified in UsedDominators, it will not be adjusted. What is more, if the connected component is an equally linked one, it will not cause deeper iterations and will be added into Candidates after it is adjusted. After all CUs in current Dominator are handled, the first item of Candidates will be removed from it and added into UsedDominators. By this means, each component in equal linkages can act as Dominator for once, and all of these components will only be identified in UsedDominators at the end of this process. As an example, Table 1 lists the iteration steps of adjustments after the middle fuselage identified in Figs. 1 and 2 is changed, in which iteration 4 means the ending of adjustment.

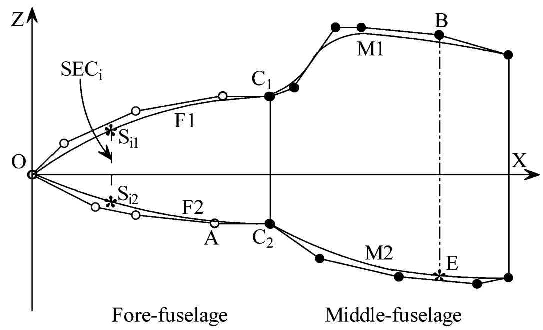
Automated Adjustment of the Components in Equal Linage

Rules and Relations

The rules applicable to two fuselage-like components in equal linkage are as follows: the components should share a common cross section to keep geometric continuity, and the change of that common cross section in either component will result in an identical change in the other component. Obviously, implementation of these rules must be based on the way of modeling a fuselage-like



a) Initial status



b) Status after automated adjustment

Fig. 3 Illustration of automated adjustment between fore fuselage and middle fuselage.

component. In SEACD, control points of plan profiles and section curves are fundamental factors constructing final two- and three-dimensional models,[11] so that determining new positions of relevant control points is the most important part of automated adjustment.

To eliminate the error between the adjacent cross sections of connected components, a step called preadjustment is conducted once the designer assigns an equal linkage. In this step, the fore or aft cross section of one component is adopted as the common one, and the corresponding cross section of the other component is forced to be the same with it. At the same time, the adjacent profiles of them will also have several common control points.

Equal linkage between the fore fuselage and middle fuselage is used to exemplify the detail relations for automated adjustment. Figure 3 illustrates the simplified control points and profiles of fore fuselage and middle fuselage in the left view, in which profiles F1 and F2 belong to fore fuselage, and M1, M2 belong to middle fuselage. Figure 3a represents the status right after preadjustment, whereas Fig. 3b represents the final status after control points of F1 are interactively changed by the designer. The transition from the initial to the final status needs the following five steps.

The first step is automated adjustment within fore fuselage, which means the other profiles and all cross sections of fore fuselage will be adjusted according to the variation of common control point C_1 on F1. As a random control point of F2, point A will be moved horizontally according to

$$\frac{x_A - x_{\text{fore}}}{x_{\text{com}} - x_{\text{fore}}} = \frac{x_A^* - x_{\text{fore}}^*}{x_{\text{com}}^* - x_{\text{fore}}^*} \tag{1}$$

where x_A and x_A^* are former and new X coordinates of point A (the superscript of asterisk always represents a new value in this paper), x_{fore} and x_{fore}^* are forebody stations of fore fuselage, and x_{com} and x_{com}^* are body stations of the common cross section.

New profiles can be calculated by adjusting all of the control points of other profiles of fore fuselage in this way. To the ith cross SECtion (SEC_i) of the fore fuselage, its new body station is determined by ratio adjustment like Eq. (1). Furthermore, a boundary rectangle that is determined by the profiles and contains the section curve at that body station[11] can be calculated, and the control points of SEC_i will be stretched and scaled to match it.

The second step is initializing $\boldsymbol{\alpha}$ in corresponding CU of fore fuselage. Here, $\boldsymbol{\alpha}$ is just used to determine new Z coordinates of the control points of M1, which is the only profile that links to F1. Suppose control point B is a random one, a corresponding point D on M2 can be calculated by using X coordinate of B, and then the corresponding factor in $\boldsymbol{\alpha}$, denoted as α_β can be initialized as

$$\alpha_\beta = (z_B - z_D)/(z_{C1} - z_{C2}) \tag{2}$$

where z_B, z_D, z_{C1}, z_{C2} are Z coordinates of B, D, C_1, and C_2, respectively. In this equation, the height between C_1 and C_2 is used as the reference to ensure reasonable inner volume after adjustment.

The third step is adjusting all other profiles of the middle fuselage except for M1. Because the Z coordinate of C_2 will not be changed, the control points of M2 are just moved horizontally by ratio adjustment.

The fourth step is calculating new M1. According to new X coordinate of B got by ratio adjustment, a new corresponding point E on M2 can be calculated. Thus, new Z coordinate of B is

$$z_B^* = \alpha_B \left(z_{C1}^* - z_{C2}^*\right) + z_E \tag{3}$$

where z_E is Z coordinate of point E.

Finally, based on the new profiles, cross sections of middle fuselage should also be moved, stretched, and scaled to generate new three-dimensional surfaces of middle fuselage.

Brief Discussions

If only a series of cross sections are used to model a component and no plan profile is defined, the displacement of common cross section should cause automated adjustment. Neglecting all control points, Fig. 3 can be used again to exemplify this problem. Suppose the cross sections of fore fuselage should be automatically adjusted because the designer displaces the common cross section in middle fuselage. The relation between original and new body stations of SEC_i is also determined by ratio adjustment. Its range along Z axis is determined by the positions of S_{i1} and S_{i2}, which are adjusted by taking the length between C_1 and C_2 and displacements of them as references.

In some cases, other parameters are also applicable references for calculating necessary scales. For example, the maximum width of fuselage can be used to scale control points or cross sections along Y direction, which will be useful when this parameter is adopted as a design variable for optimization.

The presented measures still have two drawbacks needing further enhancement. First, sharing cross sections only aims at keeping the linkage of two connected components, whereas higher-order geometric continuity between their surfaces must ask for more sophisticated algorithms of computer aided geometric design. Second, if three or more components are adjacent, it will be much harder to make them share one common cross section.

In fact, although it seems that relating parameters of two connected components is easy to implement, the practical conditions can be far more complex and variable, so that more than one way of defining rules and relating parameters could be proposed, no matter for equal linkage or for datum/attachment. What is more, there are also some other systems that permit the user to define similar two-way connections, for example, Design Sheet[15,16] can represent a design model as algebraic constraints between variables for doing cost and performance tradeoff studies; ADAMS[17] allows for defining assemblies and constraints between mechanical parts for dynamic simulation. Consequently, defining more rules should be an important task of future investigation on automated scheme adjustment.

Automated Adjustment of the Components in Datum/Attachment

Selection of Reference Points for Adjustment

Considering the diversity of components in datum/attachment, a basic rule is used to guide automated adjustment of the attached ones: the logical or topology relationship between the datum and attached components should be kept after the change of datum. For example, wing fuel tank should always be within the wing, and horizontal tail mounted on vertical tail should not depart from the latter.

For the purpose of improving uniformity, adjustable parameters of attached components, no matter widths, lengths, diameters or angles, are turned into the positions of a series of spatial points that are called reference points. In another word, the coordinates of reference points are used to extract the parameters controlling position and shape of an attached component. According to types of attached components, reference points can be selected as follows:

1) Reference points of a wing fuel tank are corners of the trapezoid representing its planform, which can ensure that the fuel tank is contained inside of the wing. In fact, this way is also applicable to restrict the positions of control surfaces and such structures as ribs and spars.

2) A landing gear in SEACD is simplified as a strut plus one or more wheels, and the reference point on it is the topmost point of the strut. Adjustment of this point will not only result in the movement of strut and wheels, but also stretch or shorten the length of strut.

3) Dimensions of a standard component are predefined in corresponding databases, so that the designer can only displace it by changing the position of a base point on it, and this point is selected as the reference point.

4) Nacelle is the only attached fuselage-like component in the example aircraft, and only one reference point is selected for it, so that it could always contain the engines when it is moved. For simplicity, this point is the center of the boundary rectangle at the minimum body station of the component.

5) To a wing-like component, the leading-edge point of root section should be selected, so that the component can be moved as a whole. In the example aircraft, because root chord of horizontal tail should be scaled to ensure that it is always mounted on vertical tail, the trailing-edge point of its root section is also selected. By contrast, the pylon does not have such a point because it must have proper longitudinal length to hold the nacelle.

Relations Between Reference Points and the Datum

Suppose the parameters of an attached component can be described as $\boldsymbol{P}\{P_1, P_2, \ldots, P_i, P_{i+1}, \ldots, P_m\}$ and P_1 to P_i need to be adjusted. It should be turned into $\boldsymbol{P}\{\boldsymbol{RP}_1, \boldsymbol{RP}_2, \ldots, \boldsymbol{RP}_j, P_{i+1}, \ldots, P_m\}$, in which $\boldsymbol{RP}_k\{x_k, y_k, z_k\}(k = 1, 2, \ldots, j)$ represents the coordinates of a reference point R_k. Thus, only the relation between $\boldsymbol{RP}_k$ and the datum component needs to be investigated. Based on the methods of modeling wing-like components and fuselage-like components, boundary rectangles are used to simplify the presentation of relative position between a reference point and the datum.

As shown in Fig. 4, the boundary rectangle of a wing-like component contains the wing section at the spanwise position equaling to y_k. In the factor list of $\boldsymbol{\alpha}$, assuming $\alpha_{k1}, \alpha_{k2}, \alpha_{k3}$ are items corresponding to $\boldsymbol{RP}_k$, they can be initialized as

$$\alpha_{k1} = \frac{(y_k - y_{\text{in}})}{(y_{\text{out}} - y_{\text{in}})} \tag{4}$$

$$\alpha_{k2} = \frac{(x_k - x_{\text{fore}})}{(x_{\text{aft}} - x_{\text{fore}})} \tag{5}$$

$$\alpha_{k3} = \frac{(z_k - z_{\text{low}})}{(z_{\text{up}} - z_{\text{low}})} \tag{6}$$

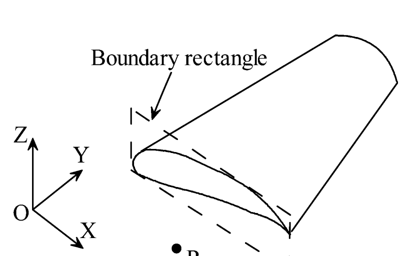


Fig. 4 Illustration of reference point and boundary rectangle.

where y_{in} and y_{out} are spanwise positions of the wing sections at root and tip, x_{fore} and x_{aft} determine longitudinal range of boundary rectangle, and z_{low} and z_{up} determine its range along Z direction. The wing-like component shown in Fig. 4 is a horizontal one, but it is quite similar to deal with a vertical one.

Once the wing-like component is changed, we can get new values of y_{in} and y_{out} (denoted as y^*_{in} and y^*_{out}), and then the new value of y_k should be first calculated as

$$y_k^* = \alpha_{k1}\left(y_{\text{out}}^* - y_{\text{in}}^*\right) + y_{\text{in}}^* \tag{7}$$

According to y_k^*, a new boundary rectangle can be constructed. Thus, new values of the other two coordinates of the reference point, denoted as x_k^* and z_k^*, can be calculated by using α_{k2}, α_{k3} and parameters of the new boundary rectangle.

Similarly, if the datum is a fuselage-like component, X coordinate of R_k is associated with its minimum and maximum body stations, and y_k^* and z_k^* are calculated by using ranges along Y direction and Z direction of corresponding boundary rectangle.

After automated adjustment, the attached component is described as $\boldsymbol{P}\{\boldsymbol{RP}_1^*, \boldsymbol{RP}_2^*, \ldots, \boldsymbol{RP}_j^*, P_{i+1}, \ldots, P_m\}$, in which $\boldsymbol{RP}_k^*\{x_k^*, y_k^*, z_k^*\}$ represents new coordinates of R_k.

Interactive Modification with Automated Scheme Adjustment

After the connection net shown in Fig. 2 was constructed, the business jet turned from the original scheme shown in Fig. 1 to the preadjusted one shown in Figs. 5a and 5b, in which the preadjustments among fore fuselage, middle fuselage and aft fuselage have been accomplished. Because the connections between fuselage-like components and seats are omitted in this research, the passenger seats are hidden in Fig. 5 for clarity.

To validate the effectiveness of automated scheme adjustment during interactive modification, several components were changed by the author following the steps listed in Table 2. In each step, the connected components that can be identified from connection net were automatically adjusted by using the rules and measures just presented. The process of adjustment caused by changing middle fuselage was just consistent with the iteration steps listed in Table 1.

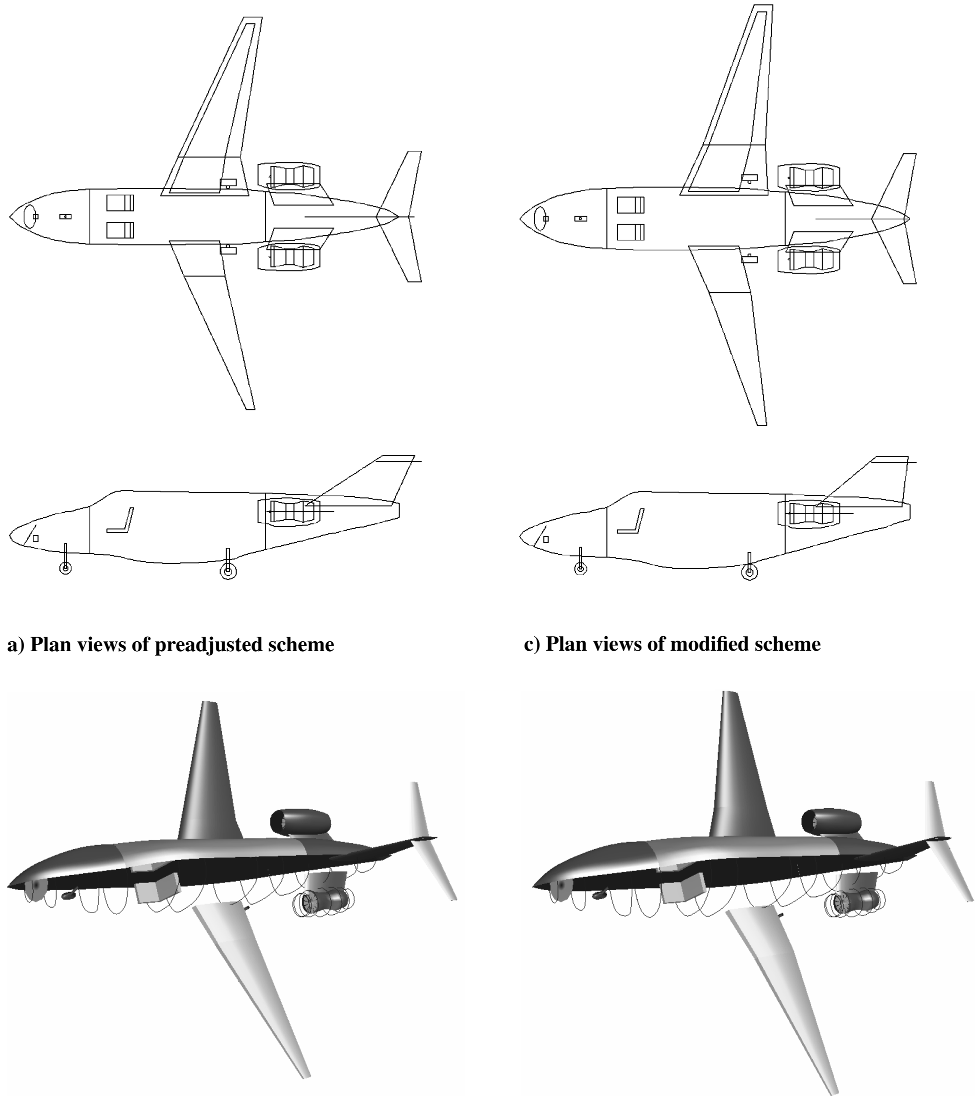
After all modifications and corresponding automated adjustments, surfaces of relevant components were also regenerated and a three-dimensional model of the concept was updated, then the concept turned to the one shown in Figs. 5c and 5d. It can be seen that a lot of work was fulfilled by the system instead of by the designer, for example, increasing the widths of fore fuselage and aft fuselage according to middle fuselage's change, as well as increasing the heights of middle fuselage and aft fuselage according to fore fuselage's change. Moreover, relations among the components were kept reasonable through such adjustments as scaling fuel tanks and moving horizontal tail.

Optimization with Automated Scheme Adjustment

The effectiveness of automated scheme adjustment during optimization was also validated. In this research, a technique called

Table 2 Steps of conducting interactive modification to the concept

Major steps	Operations	Adjusted components
1	Reduce the length of middle fuselage and increase its width by changing the profiles in top view	Fore fuselage, aft fuselage, nose landing gear, pylon, nacelle, engines
2	Change the position and spanwise length of inboard wing; reduce the sweep of outboard wing	Inboard fuel tank, outboard fuel tank, main landing gear
3	Reduce the sweep of vertical tail	Horizontal tail
4	Increase the height of fore fuselage by changing its lower profiles in left view	Nose landing gear, middle fuselage, aft fuselage, pylon, nacelle, engines



a) Plan views of preadjusted scheme c) Plan views of modified scheme

b) Three-dimensional model of preadjusted scheme d) Three-dimensional model of modified scheme

Fig. 5 Illustration of interactive modification with automated adjustment.

"integrated multidisciplinary optimization" was utilized. Reference 13 depicts this technique in detail, and it also introduces some early considerations on automated adjustment.

The preadjusted scheme shown in Fig. 5 was used as the start point for optimization. In addition to SEACD, the utilized software for optimization includes iSIGHT[18,19] and an Euler-method based code called MGAERO.[20] By taking the takeoff weight W_{to} and lift-to-drag ratio K as measures of merit, a single global criterion of the problem was constructed as

$$\text{Minimize} \qquad F = C_w(W_{\text{to}}/W_{\text{toi}}) - C_a(K/K_i) \tag{8}$$

where W_{toi} and K_i are initial values of W_{to} and K, C_w, and C_a are weight factors and their values were set as 0.6 and 0.4, respectively. In this study, W_{to} was calculated by using empirical formulas,[1,21] and K was predicted with MGAERO. Because of the capability limitation of SEACD, only takeoff wing loading and fuel weight were used as constraints.

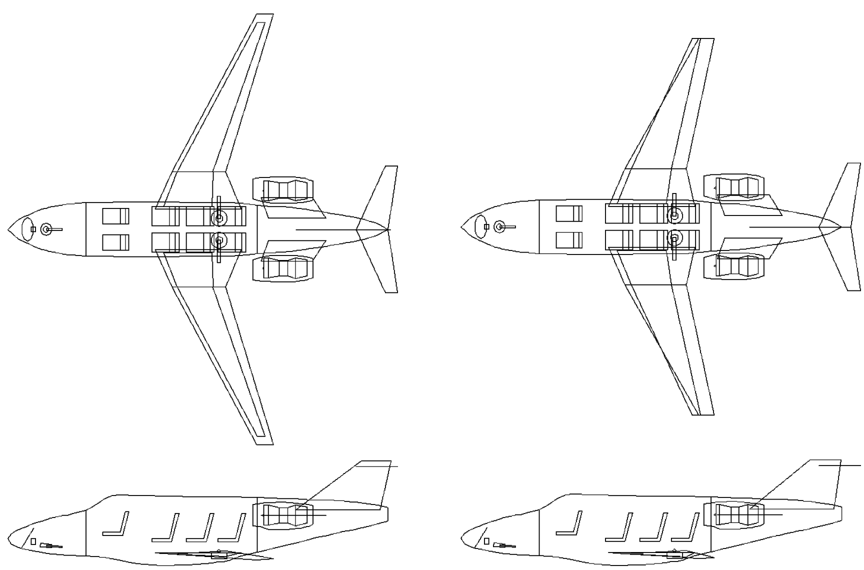
For comparison, two optimization tasks were applied to this problem. The first task was a combination of Latin hypercubes sampling, Kriging model, and multi-island genetic algorithm that are supplied in iSIGHT,[19,20] and the connection net shown in Fig. 2 functioned in this task. In detail, a design of experiment with Latin hypercubes sampling was conducted before optimization. To reduce the computing time of optimization with genetic algorithm, the 100 samples were used to construct a Kriging model that can approximate exact analyses. Thus, only about 50 exact analyses were conducted among the total 40,102 runs during optimization. The second one only used an adaptive simulated annealing algorithm[7,19] with 60 runs, and all connections were cancelled before optimizing the preadjusted scheme to disable automated adjustment in this task. Because optimization technique is not the focus in this problem, some detailed settings of each task are omitted here.

Both tasks brought optimized solutions, and the plan views of them are shown in Fig. 6. Main data of the initial and optimized concepts are listed in Table 3, from which it can be seen that the design variables are just parameters of datum components, whereas most parameters of attached component are too trivial to be set as design variables. In particular, if a parameter belonging to an attached component is determined by positions of reference points, for example, length of the root chord of horizontal tail, it should not be chosen as a design variable to avoid the interference between automated adjustment and the change made by optimization algorithms.

According to the values of global criterion listed in Table 3, the optimized concept gotten from the first task (denoted as Opt1) is better than the one gotten from the second task (denoted as Opt2). More importantly, Opt2 is unacceptable because the components that are not directly controlled by optimization algorithm were not adjusted, which inevitably leads to unreasonable interferences and detachments, such as interference between the wing and wing fuel tanks and detachment between the vertical tail and horizontal tail

Table 3 Main data of initial and optimized concepts

Parameter, units	Allowable range	Initial concept	Optimum of the first task	Optimum of the second task
Values of global criterion	——	0.200	0.026	0.130
Design variables				
Sweep of inboard wing, deg	20–30	25.00	24.74	24.03
Taper ratio of inboard wing	0.60–0.85	0.70	0.62	0.71
Sweep of the outboard wing, deg	20–30	25.00	28.17	29.53
Taper ratio of outboard wing	0.20–0.45	0.30	0.31	0.25
Spanwise length of outboard wing (one side), m	4.0–5.5	4.75	5.49	4.50
Sweep of vertical tail, deg	50–62	57.00	53.08	50.72
Taper ratio of vertical tail	0.30–0.45	0.37	0.36	0.37
Sweep of horizontal tail, deg	20–30	26.00	24.38	24.80
Foremost longitudinal position of pylon's root section, m	8.7–9.2	8.95	9.03	9.13
Data of attached components				
Volume of wing fuel tanks, liter	——	2269.66	2164.85	2269.66
Foremost body station of nacelle, m	——	8.43	8.51	8.43
Foremost longitudinal position of engines, m	——	8.77	8.85	8.77
Longitudinal position of the strut of main landing gear, m	——	7.40	7.33	7.40
Foremost longitudinal position of horizontal tail, m	——	12.40	12.08	12.40
Length of horizontal tail's root chord, m	——	1.10	1.08	1.10



a) Optimized concept of the first task **b) Optimized concept of the second task**

Fig. 6 Comparison of the results of two optimization tasks.

(as shown in Fig. 6b). In fact, much more serious interferences and detachments will appear if increasing the runs of analysis without automated scheme adjustment. By contrast, although the first task is more complex than the second one, Opt1 is usable because the attached components were automatically adjusted to keep the realism of the concept. In short, automated scheme adjustment helps designers get reasonable optima and avoid the waste of computing time and resource—especially when large-scale optimization problems are solved.

Conclusions

Based on the connection net, automated scheme adjustment supplies an artificial intelligence featured approach to organize the various components involved in a design concept. In a design system for conceptual design, it functions not only when the concept is interactively modified, but also during the process of optimization, so that the system can support designers in developing original concepts and making them evolve into reasonable optima.

Although predefining rules and relations might seem to be a trivial task, it is actually very difficult to define them with sufficient flexibility to apply to a wide variety of design problems. When properly implemented, designers using the system just need to spend little time on constructing the connection net, and then they can benefit from automated adjustment.

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