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Discussion of Knowledge-Based Design

Richard M. Wood* and Steven X. S. Bauer†
NASA Langley Research Center, Hampton, Virginia 23681-2199

A discussion of knowledge and knowledge-based design, as related to the design of aircraft, is presented. A review of several knowledge-based design activities conducted at NASA Langley Research Center is provided, and a framework for a knowledge-based design capability is proposed and reviewed. The use of information technology to improve the efficiency and effectiveness of aerodynamic and multidisciplinary design, evaluation, and analysis of aircraft through the coupling of these technologies and knowledge-based design is reviewed. The final section of the paper discusses future directions for design and the role of knowledge-based design.

Introduction

HISTORICALLY the aeronautic community can be thought of as consisting of three elements: The first element developed the fundamental tools and technologies, the second element developed the new aircraft systems using the available tools and technologies, and the third element was the government and civilian customers for the aircraft product. In the area of aircraft design, the relationship between the first and second elements has been one of mutual respect and support in which tools and technologies were developed in concert with the development of new aircraft and systems by industry. However the relationship between the tool and technology developers and the tool and technology users has eroded the past two decades. The result has been a reduction in design skills and knowledge, but at the same time an increase in the capacity to execute the design tools and processes. The new design tools and technologies that are developed are heavily skewed toward computational-based methods, such as numerical optimization strategies. This trend appears to be a means to compensate for the loss in design skills and knowledge. Whatever the motivation, the fallout of this trend is an increase in data and information generation but not an increase in design knowledge. A review of the aerodynamic literature on design supports this observation and shows a wide diversity of methods, concepts, and ideas being investigated and under development.[1–19‡] It would be expected that the increase in design data and information would result in a comparable increase in vehicle performance. However, there has been less advancement in vehicle performance compared to previous decades. In general, these new design tools and technologies fall into two groups: The largest group is clearly computationally based (CMB) designs such as multidisciplinary optimization,[15] and there are a few limited efforts investigating knowledge-based (Kb) designs such as decision-based design.[‡]

For the present discussion, the authors define CMB design as an activity that relies on a predetermined set of existing computational tools and geometric models to generate data and information that is interpreted by computer and to a lesser degree by a human. The interpretation of the data is in isolation of the historical database and is based solely in the context of the existing design activity. The structure and process of a CMB design precludes any measurable interaction or intervention by humans other than in the role as process operator or data and information reviewer. The primary assumption of CMB design is that an optimum design can be found. This implies that the optimum design knowledge and the optimum design process is fully modeled in the computer and that the computer is capable of finding the optimum design. The motivation for this approach appears to be threefold: 1) A computer is more efficient than a human. 2) A computer is more accurate than a human. 3) The total system costs are lower than using humans. However, a CMB design uses a limited set of preexisting data and information and is restricted to the use of only explicit and critical knowledge to generate designs. CMB design fails to utilize tacit and intuitive knowledge as well as other human senses and capabilities.

At the other end of the design environment is Kb design. The authors define Kb design as an activity that recognizes that all knowledge as well as passion is required to find the best design. Kb design is a knowledge- (human-) based design activity that relies on the generation and growth of a knowledge base that is used by the designer, that is, a human, to develop and guide the design activity. The data, information, and knowledge generated in the design activity are explicitly and implicitly integrated into the design knowledge base, and then the full knowledge base is interpreted in the context of all relevant data, information, and knowledge. The structure and process of a Kb design activity is human centered and, thus, cannot be directly defined. Kb design uses any tool that allows a designer to utilize their skill, senses, and knowledge in pursuit of a desired outcome. Kb design should not be confused with artificial intelligence (AI) or expert systems (ES) because those systems assume that the human knowledge and decisions can be fully modeled into a process and computerized. AI and ES systems are a form of CMB design. Note, AI and ES systems cannot be Kb because we do not know the extent of our knowledge.

A review of the available literature as well as anecdotal evidence indicates that the ability to perform efficient and effective aerodynamic and multidisciplinary design is quickly becoming a lost skill. A significant portion of this technical problem has resulted from the increased reliance by the aeronautics community on computational tools for the generation of aerodynamic analysis and design assessments[13,14] and a reduced reliance on historical data, flow physics, and fundamental aerodynamic theory and trends. The bias toward CMB design and decision making also dominates the multidisciplinary design environment. As this trend continues, the knowledge and skills that are the critical elements in the practice of aeronautic design will continue to erode as the computational tools replace the need for human thought. The authors speculate that this trend will eventually result in a stagnant design technology

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*Senior Research Aerodynamicist.
†Aerospace Engineer, Configuration Aerodynamics Branch. Senior Member AIAA.

‡Data also available online at URL: http://www.eng.buffalo.edu/Research/DBD/. See Slocum, A. H., “Passionate Axiomatic Determinisitic Design: A Plea for the Future of Designology,” Decision Based Workshop, same site. June 1998.

landscape in which we are only able to alter existing vehicles and not create new designs.

Although many still believe that computational design is the pathway to improved efficiency and effectiveness in the design environment, others are starting to question the reliance on computational tools. A portion of the design community believes that it is critical to maintain human involvement and learning in the design and analysis process[15–19] (also see earlier cited web site). Kb design is best suited to support the design community. The set of tools and technologies required to improve the efficiency of Kb design can be defined as information management tools. Examples of these tools are knowledge management systems[5,7] and virtual reality (VR) technology,[20–27] as well as other advanced information management and display technologies.

The purpose of this paper is to discuss knowledge and Kb design as related to aerodynamic design and the design of aircraft. The paper will discuss the perceived problem of a diminished design capability and the concepts of design and knowledge. A discussion of Kb design and a review of several example Kb design activities will follow. The final section of the paper will discuss future directions for design and the role of Kb design.

Problem and Solution Pathway

Problem

There are a wide variety of issues facing the engineering design community. The focus of this paper is the concern that the engineering community does not recognize that a designer is a unique and highly skilled individual whose major activity is to create and innovate. In the present environment, it is the authors' view that everyone either wants to design or to control the design process; however, there is a severe shortage of designers. The distinction between a designer and a person doing design work is equivalent to the difference between a world-renowned musician performing live in concert and a person playing a recording of the musician's performance. The first uses extreme intellect, knowledge, and passion to create, and the latter executes a routine process to recreate.

A review of the literature revealed a large number of design system types[1–9] (also earlier cited web site). The following is a list of some types: 1) AI, 2) case-based design, 3) computer-aided design, 4) concurrent design, 5) decision-based design, 6) design of experiments, 7) design synthesis, 8) design to cost, 9) ES, 10) integrated design, 11) Kb, 12) multidisciplinary analysis and optimization, 13) multidisciplinary design, 14) multidisciplinary optimization, and 15) pattern recognition design. However, there does not appear to be any organization, categorization, or classification of these systems. In addition, there are many different submethods and systems that may be listed under each of the primary types just listed. This diversity in work inhibits the focusing of resources to develop the necessary skills, capabilities, and tools to support the design needs of the future.

The present focus in design appears to be faster and cheaper,[13,14] not necessarily better. This trend has resulted in cost concerns replacing creativity, innovation, and performance. Although these present efforts may provide an apparent, that is, virtual, payoff in the near-term design process, the long-term impact can be increased product development cost and life-cycle cost as changes are made to the original design. The primary means to achieving these near-term system development cost reductions has been through the use of computer modeling of the design processes.[20] Whereas it recognized that computers are a critical tool to the engineering design community, it is a mistake to view them as the primary tool of design. However, there appears to a trend developing that, to be viewed as on the forefront of technology, there is a significant effort to automate processes and to computerize the capabilities and skills of engineers.[1,2,8] In developing these models of engineering capability, it is only possible to capture a minimal set of existing data, information, and knowledge. As a result, the majority of the knowledge and capabilities of the community are not included. A result of the computerization of the engineering disciplines is the lack of emphasis on intuitive data, information, and knowledge. This trend may result in the creative and innovative practices of the past being replaced with routine processes. Another potential by-product of this trend is that there may be a lack of understanding of final design performance, which may result in costly redesign during the development and production activities.

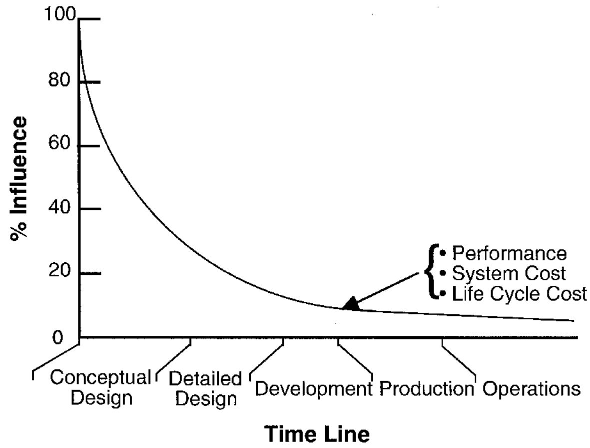

Fig. 1 Change in design influence on performance and cost with time.

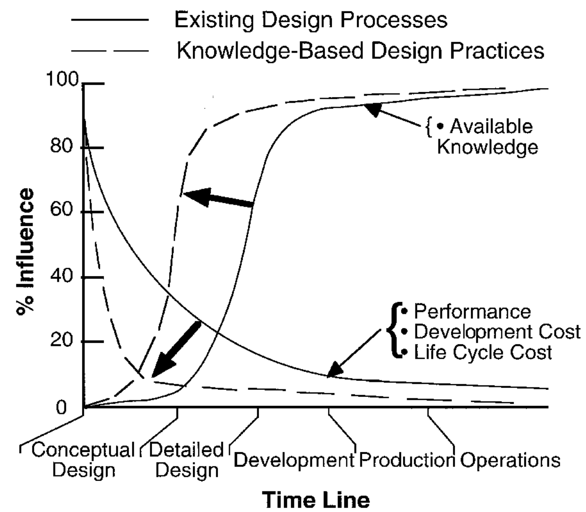

Fig. 2 Impact of knowledge on performance and cost in design.

The final issue to discuss is related to the design-development time line as shown in Fig. 1. Figure 1 shows that the opportunities to impact performance or cost of a design are heavily weighted toward the conceptual design phase where the design activity is typically guided by first-order effects and simple models.[9,14,15] A significant deficiency in the existing design practices is that only a fraction of the available knowledge for the particular design problem is associated with these methods and models. The inverse relationship between knowledge used and design impact must be corrected if significant improvements are to be achieved.

Solution Pathways

The proposed solution pathway leads through conceptual design and Kb design in three steps. The first step is to recognize that the conceptual design phase must be a highly creative, multidisciplinary activity to minimize cost and maximize design performance. Second, the conceptual design phase must be recreated into a Kb design activity that allows intellectual freedom. And the third step is the recognition that designers and not the design process are the critical element in design.[15] These ideas are notionally depicted in Fig. 2 in which performance and cost curves as well as available knowledge curves for the existing design processes and the proposed Kb design practices are shown. By inserting more knowledge into the conceptual design phase, the authors argue that greater cost and performance benefits can be achieved.

The remaining issue is whether Kb design practices or a CMB design process is more effective and efficient in integrating knowledge into a design. The argument in support of Kb design practices

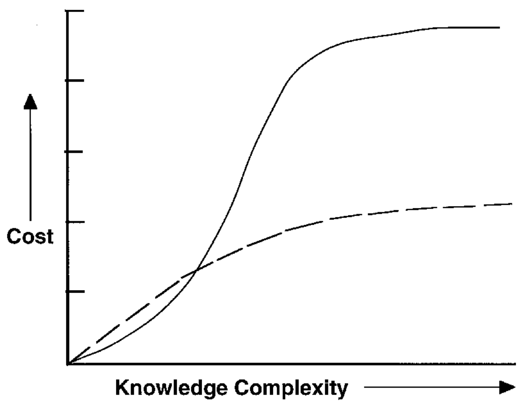

Fig. 3 Comparison of the cost of knowledge for CB and Kb design systems: ——, CB and – – –, Kb.

is shown in Fig. 3, in which the trend in cost against knowledge complexity is presented for both Kb and CMB activities. Figure 3, which represents the cost for including minimal knowledge, for example, linear aerodynamics and lift curve slope, is similar for both Kb and CMB activities; however, as knowledge complexity increases, for example, nonlinear aerodynamics, wing stall, etc., the CMB cost increases dramatically due to computational modeling, solution generation, and solution interrogation.[28] However, a much different trend can be developed for Kb design. The modeling of nonlinear aerodynamics in Kb design can be accomplished more directly by allowing the design to account for nonlinear flow constraints when defining the geometric families under consideration.

What are Design and Knowledge?

Design

Each person is actively designing throughout his or her life. We design our day, our drive to and from work, our meals, and our conversations. We design organizations, toasters, art, and airplanes. Designing is thinking, feeling, and knowing. However, to design an optimum "thing" requires a cognitive awareness of all knowledge relative to a desire. This is not achievable by a human or possible by computer. It is clear that a designer is different from one who designs. In an attempt to clarify these points and provide context for the remaining discussion, the following terms are defined.

1) Design is a concept, model, or artifact with desired performance.

2) Designer is a passionate and knowledgeable decision maker who utilizes critical and intuitive skills.

3) Designing is a creative practice that stimulates and is learned through the acquisition of knowledge.

Knowledge

The discussion and definition of knowledge is extremely difficult because it means something different to each of us. However, the authors recognize that it is critical for the remaining discussion that a definition be offered.

You do not know what you know; however, it is possible to use all that you know in the design process. To know that you do not know what you know is the first step in becoming a successful designer. This knowledge allows you to accept your intuition, that is, gut feeling, as useful knowledge and as an integrator of knowledge.

It is important to use all of one's knowledge whether or not it relates directly to design. Therefore, thoughts derived as a child affect how one thinks and the decisions one makes as an adult. An example of a thought-provoking book relative to this subject is Ref. 29 in which Geissel eloquently illustrates how anything is possible.

To define knowledge, as related to engineering, you must also define data and information. The following definitions are provided.

1) Data are a group of facts or statistics that have not been assigned meaning.

2) Information is data that has been assigned meaning.

Table 1 Knowledge matrix

Criterion	Yes	Maybe	No
Critical (C) criterion: do results look convincing	C+	Co	C−
Intuitive (I) criterion: do results feel right	I+	Io	I−

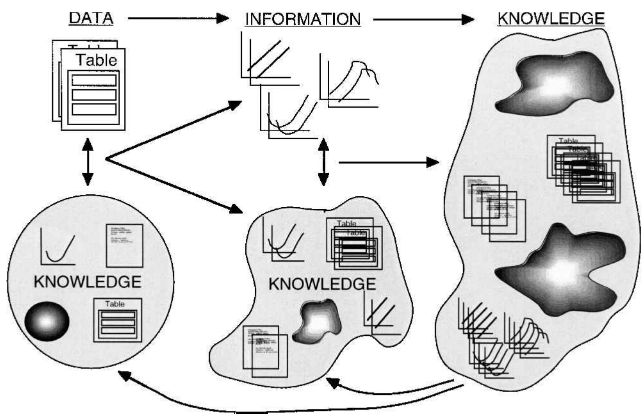

Fig. 4 Process of changing data to knowledge.

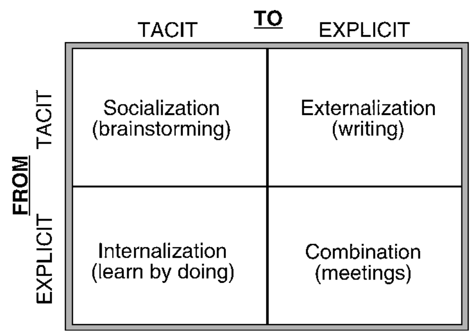

Fig. 5 Four modes of knowledge creation by Nonaka and Takeuchi,[5] where tacit is implied but not expressed (subjective) and explicit is clearly developed meaning (objective).

3) Knowledge is the sum of what has been perceived and learned that allows for the generation of information.

The interrelation between data, information, and knowledge is presented in Fig. 4. Figure 4 shows that data are operated on by knowledge to produce information and a new set of knowledge. The new knowledge is combined with information to create knowledge. This knowledge set is then used in the interaction with new data and information sets. Note, whereas both data and information are explicitly defined, knowledge is both explicit and implicit.

Another important aspect of knowledge creation is the four modes of knowledge creation introduced by Nonaka and Takeuchi[5] in 1995 (Fig. 5). In this model, there are two basic types of knowledge, tacit and explicit. Nonaka and Takeuchi state that knowledge is created by the conversion of tacit to both tacit and explicit and from explicit to both tacit and explicit. Relating these thoughts to the CMB and Kb design, we see that CMB makes use of only two modes: tacit to explicit and explicit to explicit knowledge steps, whereas Kb uses all four modes.

The final knowledge concept is the notion of a knowledge matrix (Fig. 6 and Table 1), which is borrowed from the work of Margolis[30] (also see Ref. 7) on a cognitive model he termed the "Belief Matrix." Margolis states that there is tension between critical and intuitive scrutiny to a question and the yes (+), no (−), and maybe (○) answers to the critical and intuitive question form nine affective states. In his model, a yes answer + to both the critical and intuitive questions is the knowledge affective state, upper left corner of matrix. For this discussion, the nine affective states of Margolis have been renamed to reflect levels of knowledge awareness. In the

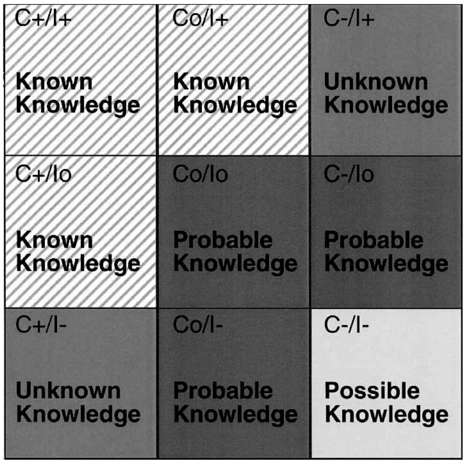

Fig. 6 Knowledge matrix.

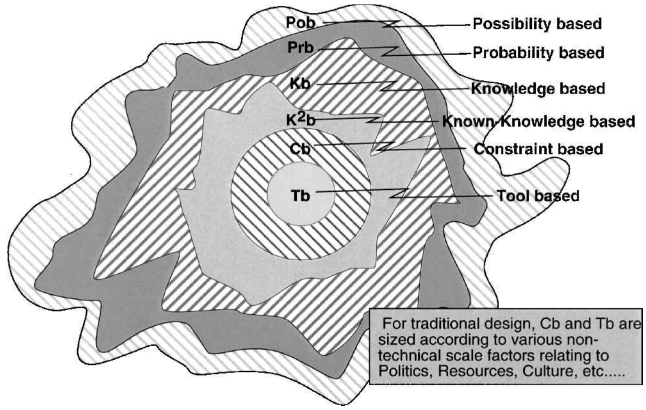

Fig. 7 Design space model.

knowledge matrix, there are four levels of knowledge awareness: known knowledge, unknown knowledge, probable knowledge, and possible knowledge. These states reflect the concept that "all" that is possible to be known can be known. The important design aspect of this concept is that in typical design systems only the critical (C+)/intuitive (I+) known knowledge state is utilized. However, in some design systems, all of the C+ states are used due to an increased reliance on computational results. The benefit of Kb design is that all nine states are used.

Kb Design

Various forms of Kb systems have been discussed within the literature. These typically take the form of AI and ES that attempt to capture and model knowledge in a database format. However, the use of Kb in the context of design and designer-driven practices, defined herein, has not been previously discussed. Kb design is one that is practiced by a designer who relies on intellectual optimization and thought experiments in developing a particular solution pathway. The designer respects simplicity, recognizes that nature and its laws are continuous, and understands that rebellion and debate are necessary tools. Another description that reflects this view is that expressed by Slocum in his position paper for the Decision Based Design Workshop located at www.eng.buffalo.edu/Research/DBD/: "Designers have a bio-neural-net programmed for deterministic axiomatic thought while simultaneously achieving rapid-fire multi-techno happiness enhancement." "Designers need tools that catalyze their thoughts . . . and harness an attribute that no neural net can dream of, a passionate lust to create a most awesome amazing orgasmic design."

Designer's Practice

The designer begins the design challenge by taking an infinite view of the problem. This first step is critical and may be viewed as designing the design. Designing the design provides context and content but does not constrain or inhibit. This perspective is shown in the model of the design space shown in Fig. 7. The design space model shown has six regions depicted as successively smaller regions. This representation is consistent with the present (traditional) design process. However, for a Kb design, this is only true for possibility, probability, knowledge, and known knowledge spaces. For Kb design, the constraint-based (Cb) and tool based (Tb) design spaces are not scaled and are not assumed to reside within the known knowledge-based (K^2b) design space but are characterized as concept families. Another point to note is that the constraint and tool spaces are scaled by various factors such as politics, resources, and culture. In addition, the relative size of the constraint and tool spaces may reverse from that shown and they may extend outside of the K^2b into the Kb, probability-based (Prb), and possibility-based (Pob) spaces. The goal in the practice of Kb design is to utilize tools and constraints as influence factors to use as much of the design space as possible.

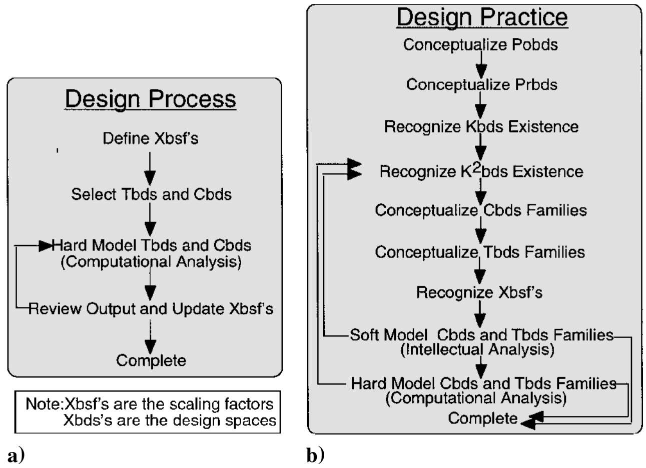

Fig. 8 Design process and design practice models.

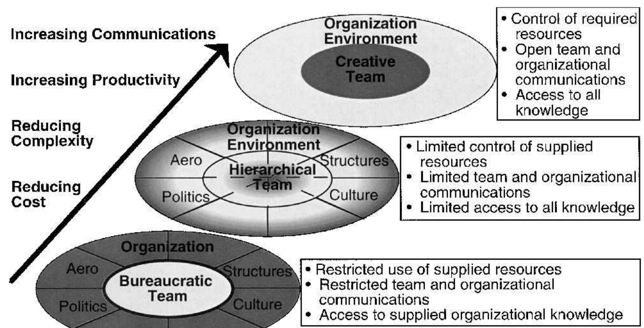

Fig. 9 Team types.

The next issue faced by the designer is the dilemma between using a design process or design practice, as shown in Fig. 8. As one would expect, the designer prefers the design practice as shown in Fig. 8b. However, politics, resources, and culture attempt to drive the designer to a process as shown in Fig. 8a. The major differences between the two are that the process is an inside-out activity, which knowingly utilizes only a small section of the design space, whereas the practice is an outside-in activity, which utilizes the full design space. The process represents the scale factors (Xbsf's), constraints, and tools as hard models, whereas the practice recognizes and conceptualizes the existence of these desires and chooses the degree of acceptance.

The final challenge the designer faces is the work environment or team structure. Figure 9 shows the three of the team types that exist: bureaucratic, hierarchical, and creative. The bureaucratic team is formed by the organization and exists as an element of the organization. This team is recognized as being in competition with other elements of the organization and must operate within the organizational policies and culture. The hierarchical team is formed by the participating elements of the organization to perform a task of mutual benefit. This team is supported as long as it is recognized as adding value to the individual elements of the organization. Those who have a shared passion and are committed to achieving success form the creative team. The creative team operates within the organization environment but not for the organization. The preferred team is the creative team; however, it is not one that is typically supported by an organization. The characteristics of a creative team are increased communications, productivity, and reduced complexity and cost compared to the other two team types.

The ability to create the preferred designers' environment requires the recognition that knowledge is the most valued commodity and that creativity and innovation are critical. If these three characteristics are present, then Kb can achieve success.

The next three sections of the paper will review the results of three conceptual design activities at NASA from 1985, 1990, and 1995 that used Kb design in a creative team environment. The authors recognize that the following design activities lack the complexity and sophistication of vehicle design and development work in industry; however, they are useful and relative for discussing the concept of Kb design.

Natural Flow Wing (NFW) Design

The natural flow wing[31] (NFW) design activity took place in 1985 with a team of four engineers representing the disciplines of aerodynamics, structures, survivability, and manufacturing/maintainability. The design activity focused on the development of Kb design rationale for including nonlinear effects into the conceptual design phase of the multidisciplinary design of highly efficient multipoint-design wings. The design approach was derived from data extracted from experimental observations and computational analysis. The proposed design rationale is based on criteria from the following disciplines: aerodynamics, structures, survivability, and manufacturing/maintainability. The combination of criteria for these disciplines indicated that the optimum wing would be a symmetric, planar geometry without breaks to the outer mold line.

The first step in the design is to develop an understanding of the various layers to the design space presented in Fig. 7. A description of each of these design space layers is presented in Table 2. The Pob design space is characterized by all three-dimensional shapes with smooth and continuous geometry. Recognition of the need for three-dimensional geometry is based on volumetric and structural requirements of the design and the need for smooth and continuous geometry addressing aerodynamics and survivability considerations.

The second layer is the Prb design space. Within this space, we add to the Pob design space description by calling for a benign pressure loading and an aerodynamic insensitivity to volume. These two additional descriptors characterize the expected aerodynamic performance of the design and provide a vision of a design with a very robust performance map.

A review of the descriptors for the Kb design space shows that low drag, no movement of the aerodynamic center, and increased volume are added to the Prb design space characteristics. These new characteristics add to the vision that the final design will be very robust and have excellent aerodynamic characteristics.

Table 2 Description of NFW design space

Design space	Description
Pob	All three-dimensional shapes with smooth and continuous geometry.
Prb	Pob plus benign pressure loading, aerodynamic insensitivity to volume changes.
Kb	Prb plus drag lower than linear theory minimums at all Mach numbers and angle of attack, no aerodynamic center travel, increased volume over existing designs.
K^2b	Kb plus geometry matched to observed three-dimensional pressure loading pattern for swept wings.
Cb	Scale/volume required for mission.
Tb	Analytic geometry definition capability.

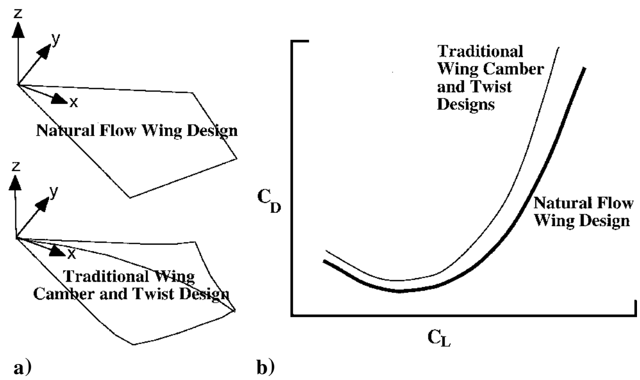

Fig. 10 Details of the NFW design study.

The next design space is the K^2b design space, where design guidance is provided. For this design space, the intent is to take advantage of experimental and computational data observations of three-dimensional pressure loadings over similar planforms and then to use these contours as maps to guide the reshaping of the wing geometry to match the observed three-dimensional pressure loading.

The final two elements are the Cb and Tb design spaces. For a traditional design, the Cb and Tb design spaces are assumed to reside within the K^2b design space and are sized according to nontechnical factors such as politics, culture and resources. However, for Kb design, the Cb and Tb design spaces are not scaled and are not assumed to reside within the K^2b design space but are characterized as concept families that are used to guide the design. For this design, the Cb design space description is that the volume will be sufficient to fly a candidate mission, and the Tb design space will have an analytic geometry definition capability.

With the Pob through Tb design spaces, thoughts, and visions in hand, a design activity is initiated and managed by the designer. The resultant design is shown in Fig. 10. Shown in Fig. 10a are sketches of the NFW design and a traditional design. Note that the NFW design is flat and planar, whereas the traditional design is characterized by having camber and twist. This geometric characteristic of the NFW design is critical in satisfying the survivability requirement. Another characteristic of the NFW design is the increased volume compared to the traditional design. The resulting performance is shown in Fig. 10b in the form of a drag polar. The NFW design had lower drag at all lift coefficients than the traditional design. These results indicate that the NFW design achieved all of the stated objectives and produced a new aerodynamic shape family that provides unique aerodynamic and survivability performance.

Advanced Aircraft Control Effector (AACE) Design

The advanced aircraft control effector (AACE) Design activity[32] was conducted in 1990 with a team of 11 engineers representing aerodynamics, electromagnetics, controls, structures, propulsion, and weights. AACE focused on the design of advanced aircraft control effectors that allow for the development of low drag, highly agile aircraft that are affordable and satisfy future observability requirements. In pursuit of this goal, it was recognized that several new concepts/technologies would be required. These concepts were characterized as passive flow control devices and/or microsized. Another concept introduced was the notion of designing the planform as a zero-order control effector and to control the planform performance through the use of micromotion boundary-layer control devices.

As was done in the NFW design activity, discussed earlier, the first step in the AACE design was to develop an understanding of the design space. The list of characteristics for each of the six design space layers is shown in Table 3. A review of these descriptions shows that the design spaces are notionally described and that each successive design space builds on the description of the previous space. Another characteristic of Kb design is the use of aggressive performance objectives as shown in Table 3. An interesting point was the absence of any significant Cb or Tb description. The Cb and Tb design space

Table 3 Description of AACE design space

Design space	Description
Pob	All mechanical, fluidic, pneumatic, thermal, acoustic, etc., flow management and control effector concepts. All vehicle planform concepts comprising straight edges.
Prb	Pob plus simple and lightweight. At least linear lift and pitching moment up to 50-deg angle of attack.
Kb	Prb plus a minimum of 50% improvement in aerodynamic performance and a 50% reduction in volume requirements and weight.
K^2b	Kb plus steady-state operation. Planar geometries with aligned edges.
Cb	Must be NEW ideas.
Tb	None

Table 4 Description of HSR design study

Design space	Description
Pob	All three-dimensional shapes with smooth and continuous geometry defined by the existing wing planform, vehicle structural volume, and engine locations.
Prb	Pob plus planar edges, benign pressure loading, aerodynamic insensitivity to volume changes.
Kb	Prb plus drag lower than linear theory minimums at all Mach numbers and angle of attack, no aerodynamic center travel, increased volume over existing designs.
K^2b	Kb plus geometry matched to observed three-dimensional pressure loading pattern for swept wings.
Cb	Scale/volume required for mission.
Tb	Analytic geometry definition capability.

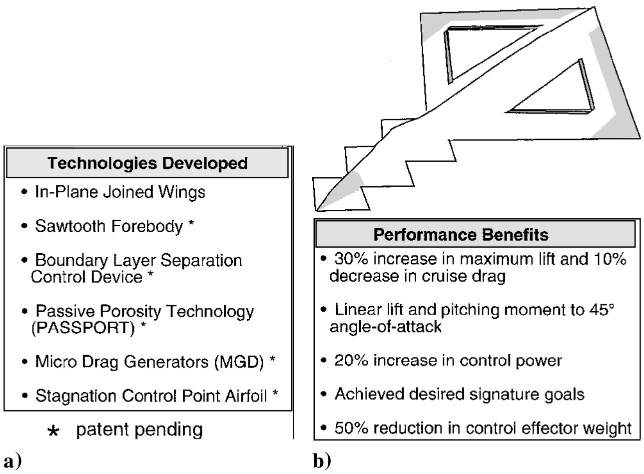

Fig. 11 Details of the AACE wing design study.

Table 5 Details of HSR study

Configuration	Δ Volume, %	ΔC_L	ΔC_D
Numerical optimization	0.00	0.0	0.0000
NFW	+4.82	0.0	−0.0003

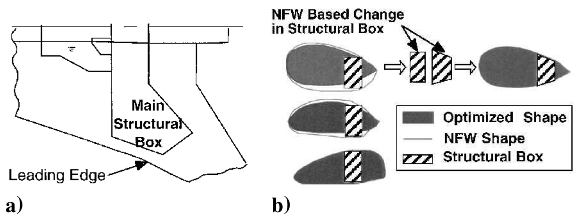

Fig. 12 Details of HSR design study.

for the AACE activity allowed freedom for the creation of new technologies and concepts that were required to meet the performance objectives.

Presented in Fig. 11 are the resultant technologies developed and performance benefits achieved in the AACE design. A graphic of the AACE design concept is also shown in Fig. 11. The AACE activity produced a large number of new technologies of which five are patent pending. These technologies ranged from advanced planform concepts to micro-boundary-layer control devices. The ability of these devices in achieving the stated goal is itemized in Fig. 11b. The AACE activity produced improvements in aerodynamic, electromagnetic, control, and weight compared to traditional technologies.

High Speed Research (HSR) Arrow-Wing Design

The high-speed research (HSR) arrow wing design activity[33] was conducted in 1995 with a team of six engineers representing the disciplines of aerodynamics, structures, propulsion, controls, and weights. This design activity was the first attempt to apply the military-based NFW design philosophy to a commercial design problem. The starting point for this effort was a numerically optimized, Euler- (and Navier–Stokes-) based arrow wing design within the HSR program. The focus of the Kb design was to reduce the supersonic and transonic drag while increasing volume. It was expected that the NFW design approach would produce the characteristic flat wing and eliminate much of the waviness of the conventionally optimized CMB designs.

As with the two preceding examples, the first step in the design was to characterize the design space. Note that, for this design, the HSR program had very strict constraints and requirements on volume, thickness, spar thickness and location, leading-edge radius, fuselage incidence, engine location and orientation, etc. However, the Kb design activity did not hold these as rigid values as was done by other HSR design teams. This design study recognized the HSR constraints as desired outcomes. As a result, a review of the design space model for this activity show the same geometric characteristics as those for the NFW design activity in Table 2, see Table 4.

Presented in Fig. 12 are the results of the HSR Kb design. Figure 12a is the wing main structural element, and Fig. 12b are the airfoil sections for the conventionally optimized wing, that is, CMB design, and NFW wing, that is, Kb design. Comparing the three airfoils in Fig. 12b shows that the NFW design has greater volume than the CMB-optimized wing. A review of the airfoils in Fig. 12b (moving from left to right) shows the inclusion of multidisciplinary effects by reshaping the structural box (cross-hatched cross section). A comparison of the performance of the two designs is given in Table 5 and shows that the NFW has three counts lower drag at the cruise point and has a 5% increase in volume.

The three examples discussed reflect the benefit of relaxing constraints and allowing creativity to have a role in the design activity. The three Kb design discussed were accomplished with less resources, compared to similar CMB design work.

Future Directions

The preceding sections of the paper have addressed the general problem of design and have reviewed some Kb design studies conducted at NASA. This section of the paper will provide an aerodynamicists view toward design, discuss some specific problems in aircraft design, and propose a solution to these problems.

Over the past decade, there has been significant growth in the use of computers in the design of aircraft, and coincident with the computational growth there appears to have been a reduction in new knowledge related to aircraft design. If this trend continues, we may reach the point where future aircraft design tools would have to be developed that require a limited understanding of aircraft design, aerodynamics, or any other discipline, and as a result we would approach Dwoyer's 1987 prediction (see Ref. 34): "If you ask me to envision what I see in the year 2020, there will be no wind tunnels.

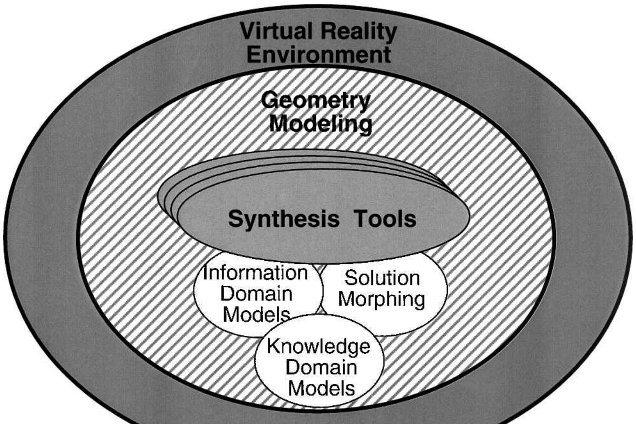

Fig. 13 VR Kb design model.

I would say we would be at the point where airplanes could be designed by rather low-paid technicians." However, this is clearly an undesirable outcome.

The present aircraft design environment is focused on computational efficiency, and within the present design environment the aerodynamicists, as well as other disciplines, have had their role reduced, in which they are unable to contribute specific design intellect and knowledge. The result is a loss in design potential. If we are to recover lost capability, the next generation of design tools and technologies must be based on the latest discipline-based design philosophies and concepts, and the tools must have the ability to capture and share knowledge. These new methods must be structured to support the creative and innovative activities of designers. Last, the design activities must not be constrained by existing technical performance boundaries and goals.

To satisfy these needs, the authors propose that Kb design tools and practices be created and defined to provide the framework for designers to reduce the design cycle time an order of magnitude and to achieve performance goals that exceed the recognized boundaries by 50%. These tools will require advanced information technology such as VR integrated into a Kb environment. A schematic of a proposed VR Kb design environment is shown in Fig. 13. The VR shell will create a designer-friendly work environment, where the design knowledge and the physical design can be accessed and integrated in real time to create new knowledge and a new design. A critical element of Kb design is the geometry modeling capability. This component of the Kb design must allow any concept or notion to be represented. Residing under the geometry shell are the synthesis tools that manage the existing knowledge as well as capture the new knowledge generated within the system. A critical element of design is the efficient modeling of the information and knowledge domains, which allow for effective transformation and morphing of these domains between problem sets.

An important characteristic of Kb design is that it must be capable of learning. This characteristic, shown in Fig. 14, shows the design cycle for a Kb design. A design activity would start with a definition of the design space and the design goal. The generation or the importing of a description (geometry model) of the concept would follow. The designer would then interrogate the knowledge domain (KD) relative to the model and stated goal. If the KD is valid for this problem, the relative information is extracted and the results are synthesized into a possible solution, and the process is repeated until the designer is satisfied. If the KD is not valid, there are two steps taken: The first is to characterize the KD relative to the problem and update the KD. The second option is to review the information domain (ID). A review of the ID takes the same form as the KD with the exception that, if the ID is not valid, the resolution is to obtain new data to feed the ID and KD models. Note that without the learning capability, knowledge would be lost, and we would spend more time and resources recreating than creating.

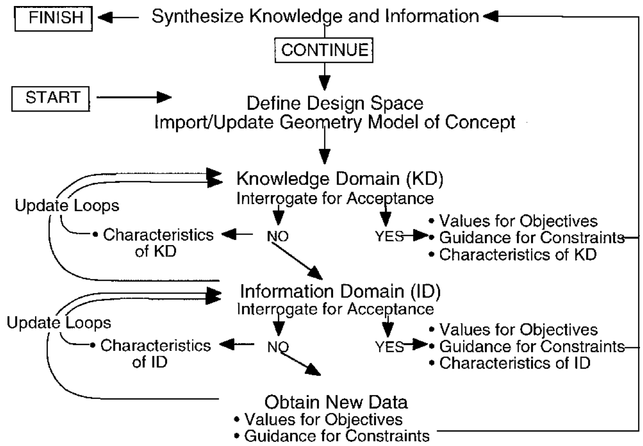

Fig. 14 Steps of the VR Kb design system.

Note that Kb utilizes both Kb models and information-based models. The transformation of data to information and then to knowledge is critical for the system to learn.

Conclusions

Design is a greatly misunderstood and undervalued practice within the engineering community. This is especially true for Kb design despite that each of us practice Kb design in our daily lives. However, when we arrive at work, we fall prey to the daily process-management routine of recreating knowledge. These random process acts must be restructured into creative and innovative practices if we are to move the design technology forward.

Relative to aircraft design, it is important to recognize that the design philosophy, not the design process, defines the design space. The design philosophy, which is developed by the designer, must not be constrained by known rules, constraints, or by computational tools. It is also important to recognize that the ability to perform conceptual nonlinear design is not contingent on the ability to obtain a computational nonlinear solution. The efficiency and accuracy of the conceptual design phase is directly related to the knowledge used; thus, we must focus on including ever greater amounts of knowledge into the conceptual design phase.

To address the need for improved design capability, the following recommendations are offered.

1) Facilitate the development of design knowledge, design skills, and design philosophy.

2) Develop learning, knowledge-management systems for designers.

3) Develop advanced data and information management tools for designers.

4) Recognize that design is a knowledge-driven activity and not a computational process.

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