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DEVELOPMENT OF A CHANGEABLE AIRFOIL OPTIMIZATION MODEL FOR USE IN THE MULTIDISCIPLINARY DESIGN OF UNMANNED AERIAL VEHICLES

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ABSTRACT

Complex systems need to perform in a variety of functional states and under varying operating conditions. Therefore, it is important to manage the different values of design variables associated with the operating states for each subsystem. The research presented in this paper uses multidisciplinary optimization (MDO) and changeable systems methods together in the design of a reconfigurable Unmanned Aerial Vehicle (UAV). MDO is a useful approach for designing a system that is composed of distinct disciplinary subsystems by managing the design variable coupling between the subsystem and system level optimization problems. Changeable design research addresses how changes in the physical configuration of products and systems can better meet distinct needs of different operating states. As a step towards the development of a realistic reconfigurable UAV optimization problem, this paper focuses on the performance advantage of using a changeable airfoil subsystem. Design principles from transformational design methods are used to develop concepts that determine how the design variables are allowed to change in the mathematical optimization problem. The performance of two changeable airfoil concepts is compared to a fixed airfoil design over two different missions that are defined by a sequence of mission segments. Determining the configurations of the static and changeable airfoils is accomplished using a genetic algorithm. Results from this study show that aircraft with changeable airfoils attain increased performance, and that the manner by which the system transforms is significant. For this reason, the changeable airfoil optimization developed in this paper is ready to be integrated into a complete MDO problem for the design of a reconfigurable UAV.

KEYWORDS

Reconfigurable system design, transformation principles, changeable systems, multidisciplinary optimization

NOMENCLATURE

AR	wing aspect ratio
C_d	airfoil drag coefficient
C_L	airfoil lift coefficient
c_p	specific fuel consumption rate (slug/lb*s)
D	drag force (lbs)
E_{CL}	time to climb (fractions of an hour)
E_{LTR}	loiter time (hours)
e	Oswald's efficiency factor
g	gravity (ft/s^2)
L	lift force (lbs)
M_{ff}	mission fuel fraction
R_{CR}	cruise range (miles)
R/C	rate of climb (ft/s)
S	area (ft^2)
s	takeoff distance (ft)
T	thrust (lbs)
V	velocity at mission segment i
W_F	fuel weight (lbs)
W_i	aircraft weight at mission segment i (lbs)
W_{TO}	takeoff weight (lbs)
η_p	propeller efficiency
ρ	air density (slug/ft^3)
μ_r	coefficient of rolling friction

1. INTRODUCTION

As the limitations of static systems become increasingly apparent, reconfigurable and changeable systems have recently been identified as a potential solution to this demand for increased performance [1]. These systems are designed to maintain a high level of performance by changing their configuration in use to meet multiple functional requirements or changing operating conditions [2, 3]. The goal of this work, and a primary contribution of this paper, is integrating the mathematics of system optimization with transformational design concepts. In doing so, the performance advantages of system transformations and reconfigurations are investigated using an unmanned aircraft vehicle (UAV) model.

Research in reconfigurability has increased dramatically over the last few years. However, such design comes at the expense of complexity, as large-scale, multidisciplinary designs must be optimized for multiple configurations. Multidisciplinary design optimization (MDO) frameworks have been developed to handle the difficulty of measuring the performance of such complex, large-scale systems [4]. Here, the original system is decomposed into subsystems, comprised of unique disciplines, which are linked together by coupling information transferred from one subsystem to another.

This paper is part of a research effort to use MDO on a system that is capable of reconfiguration to achieve optimal performance across different operating criteria. Implementing reconfigurability in a complex system is a challenging endeavor because design variables must be selected across disciplinary subsystems and across different operating states. This is also a rewarding endeavor because this complexity is relevant to real-world engineering challenges. UAVs have become an important part of military operations and are used in various missions.

In the steps towards creating a realistic reconfigurable system MDO problem, this paper focuses on the impact of allowing one subsystem to undergo reconfiguration. Limiting the number of disciplines considered in the test problem reduces the number, and coupling, of design variables. This allows the impact of different transformation principles and facilitators to be studied more closely. The airfoil subsystem model is fully developed in this paper and is used to compare the achievable performance of different UAV designs. First, a static design is considered, in which the same airfoil must be used throughout the entire mission. Next, an airfoil is considered which undergoes an irreversible adaptation, allowing only a single change to occur during the mission. Lastly, a reconfigurable airfoil is allowed to repeatedly, and reversibly, change for each mission segment to obtain optimal results.

In Section 2, reconfigurable system design research is discussed. Section 3 presents the overall research approach for the reconfigurable system MDO problem along with the specific tasks and approach for this paper. The conceptual design of the reconfigurable airfoil using transformational design tools is discussed in Section 4 before creating the mathematical model in Section 5. The results showing the advantages of a changeable airfoil are shown in Section 6.

2. RELATED WORK

The primary motivation for a reconfigurable system comes from the inherent tradeoffs incorporated when resolving the issue of conflicting objectives. Physical reconfigurations are used, after deployment, to maintain a high level of performance. This definition of reconfigurability has been further elaborated upon, stating that true reconfigurations must be repeatable and reversible [3].

Fundamentally, there have been two approaches to exploring reconfigurability. In application-based research, the concept of a reconfigurable (or morphing) aircraft is not new. Many applications investigate the design of a morphing aircraft wing and the technical challenges associated with such a task [5-8]. However, these works typically focus on a single concept and do not present a general design methodology.

Seemingly opposite to the application-based research, the engineering design community has focused on the mathematics of the optimization problem, and not explicitly on the manner by which the system changes. These research efforts span three specific areas: costing [1, 9], design variable selection [10-13], and system transitions [14-17]. Introductory reconfigurable system design research used the Decision-Based Design (DBD) framework originally introduced by Hazelrigg [18] to determine the increased costs of reconfiguration. Optimization was used to select the ranges that produced the best reconfigurable system performance. Olewnik built upon this model by using conjoint analysis to assess the component 'part-worth' for each attribute comprising a product, making it possible to calculate the product's total utility [9].

Khire and Messac introduced the Variable-Segregating Mapping-Function (VSMF) [10] to integrate the selection of adaptive and fixed design variables with the optimization of system performance. Other researchers have used design variable variations or treated morphing as an "independent variable" to determine which components should be changed, and by what magnitude [11, 12]. A constraint-based approach using system mass was recently developed by Ferguson and Lewis [13] to aid in design variable selection. If the extra component mass to achieve reconfigurability is too large, the performance advantage of reconfigurability is offset, establishing an effective system constraint.

Siddiqi [2] introduced a controls-based approach that allows designers to identify 'good' configurations the system should be able to adopt over the course of its operations. Under this approach, it is also possible to determine the likelihood of reconfiguring into a failure state from which the system can never leave [15]. A similar scheme creates action plans to execute reconfigurations in response to task changes, environmental changes, aging, and deterioration using a series of Design Structure Matrices to ensure operation [16, 17].

A missing element of these works is investigating, and defining, the manner by which a system changes form. This property – flexibility – allows a system to undergo changes in state to promote new, or enhanced, functionality [19]. Transformational principles have been established as a way to generate solutions toward changing a system's form, allowing a design to perform separate functions or improve its original function [20, 21]. Identified from analogies found in nature, patents, and marketed products, the principles and facilitators shown in Appendix A, Figure A1 create high level concepts that yield innovate solutions for changing a system's configuration.

In this paper, we take the initial steps at integrating transformation principles and facilitators into the process of embodying a reconfigurable system. Exploring the application of various transformation principles will allow for the optimal method of system reconfiguration to be determined. By pursuing a stage-gate process, an evaluation tool is created that supports the selection of potentially useful transformation options at the system level. However, determining the proper application of directives requires the construction of a system model. The next section of this paper introduces the research approach and scope of this work.

3. RESEARCH APPROACH

The results presented in this paper are part of a larger effort to formulate the multidisciplinary optimization of a complex system that allows the subsystems to individually reconfigure for optimal performance and accounts for parameter coupling of the subsystems' states. In Figure 1, the overall research approach is shown on the left and the specific tasks covered in this paper are shown on the right.

Selection of a multidisciplinary problem was based on a number of criteria such as the relevance to current engineering activities and availability of resources required for model development. For most complex engineering problems, a variety of performance objectives can be selected. Performance objectives can either be optimized individually, or a multi-objective optimization approach can be used in which each performance objective is given a relative weight based on the mission specifications.

In this paper, the focus is to define the reconfiguration of a single subsystem and show that reconfigurations improve the performance of the overall system. This is done by using transformation principles to seed concept generation activities for the subsystem's physical reconfiguration. Selected concepts are then implemented into an optimization model by the addition of reconfiguration parameters that allow design variables to physically change after the system is deployed. A 'static' design without reconfiguration parameters serves as a benchmark to which the reconfigurable designs are compared.

The stage-gate nature of the approach proposed in Figure 1 allows a designer to select the reconfigurable subsystems present in the final multidisciplinary optimization problem. While the scope of this paper is investigating whether the airfoil discipline passes the stage-gate, this step can be repeated for all subsystems so that a number of reconfigurable combinations can be simultaneously modeled in the final MDO problem. The implementation of this stage-gate is important to ensure that reconfigurability of selected subsystems will play an important role in the final MDO problem. It is unlikely for the reconfiguration of a subsystem to improve overall performance in a fully coupled MDO problem if it does not improve performance in the decoupled optimization problem. Failure to pass this stage-gate requires the selection of different subsystems for reconfiguration.

For subsystems that pass the stage-gate, their incorporation into the MDO problem will increase the complexity and computational expense associated with developing an optimal solution. From a tradeoff perspective, it will also be necessary to explore the interactions between reconfigurable subsystems. Furthermore, negative effects of reconfigurability may include increased weight and volume which may decrease performance in a fully coupled MDO problem. When considering these negative aspects, the optimization may show it is more effective to have a static system that performs a single task.

While this phase of the approach is outside the scope of this paper, developing methods to handle this additional complexity is identified as a future research question.

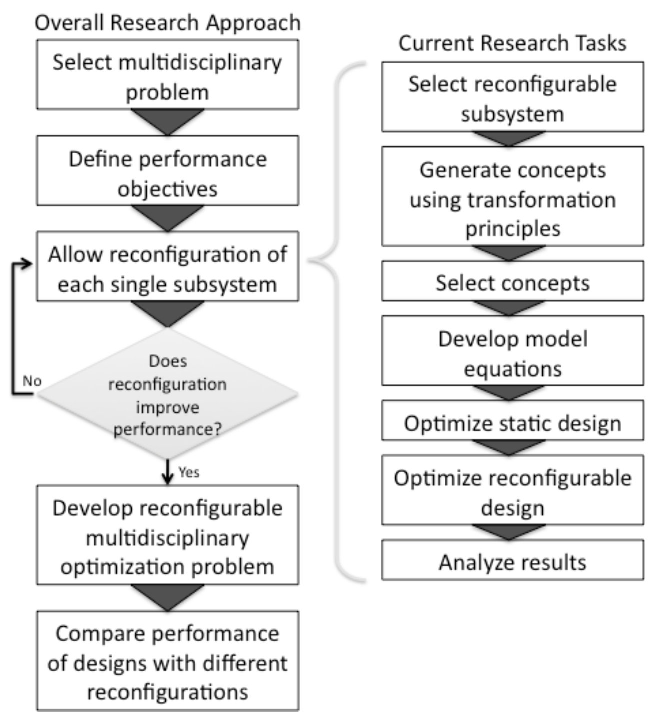


Figure 1. Research approach

4. PROBLEM BACKGROUND AND DESIGN

Aircraft flight has clear performance objectives such as maximize range, maximize endurance, minimize fuel, and others. These performance objectives can be considered simultaneously for a specific mission by using a weighted-sum objective function. For example, it might be of interest to know the maximum range that can be reached using different

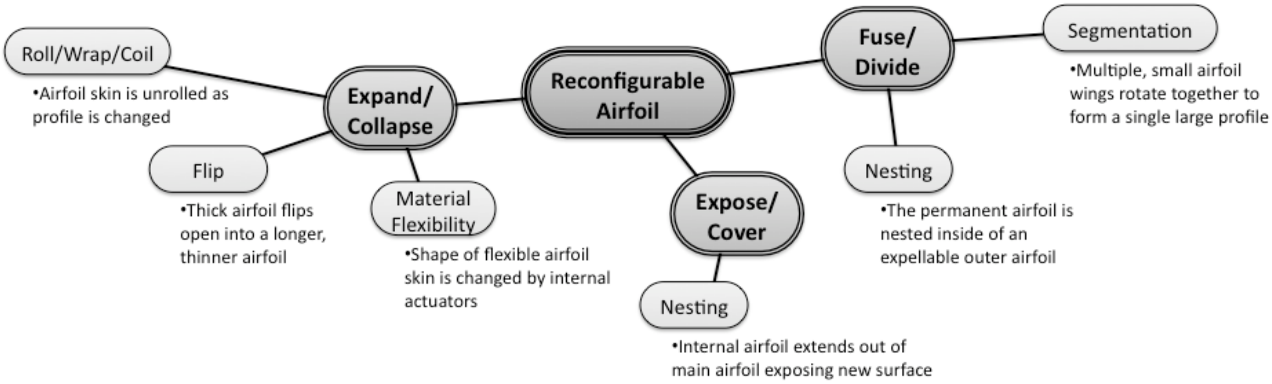


Figure 2. Mind map of concepts created from transformation principles

designs for a fixed amount of fuel.

UAV design, even at the conceptual level, requires the consideration of many subsystems that must work together to achieve controlled flight. Some of the first subsystems to consider are the aerodynamic shape of the wing, the propulsion system, the fuselage, and the interior structure that holds it all together. As the design process progresses, more detail is required as the number of subsystems continues to increase with consideration of the control surfaces used to affect the airflow around the plane, the hydraulic or electric system which manipulates the control surfaces, the avionics, positioning, and communications systems, and landing gear. Currently, modern aircraft use select transformations to accommodate two distinct states. For example, the landing gear is exposed when the plane is not flying and needs to be supported upon the ground. Upon takeoff, the landing gear is quickly folded into the plane and covered to reduce drag. Referencing the transformation principles in Figure A1, this is an example of "expose/cover."

For the UAV problem, we consider configuration changes that may be motivated by the different mission segments encountered, or by a sudden change such as a payload being dropped. As aircraft performance is strongly influenced by the shape of the airfoil, the airfoil shape is selected as the reconfigurable subsystem in this problem. Reconfiguration of the airfoil is limited to be within the design space defined by the four-digit NACA (National Advisory Committee for Aeronautics) number. The four-digit NACA series is the simplest series of airfoils and it has been in use for many years. Tools and equations are readily available that allow the detailed airfoil analysis necessary for model development.

For the optimization of the model, a physical concept is required that defines the way in which the airfoil is allowed to reconfigure. In other words, it is not reasonable to expect that any two points in the design space can be selected and made to be two states of the same system. Therefore, transformation principles and facilitators are used to develop concepts that explain how the airfoil may move between states. A mind map created during the brainstorming session for the transforming airfoil is shown in Figure 2. Transformational design methods are generally intended to aid in the design of a product that is used in distinctly different functional states such as a storage state and an operating state. In this research we use them to facilitate the design of a reconfigurable system performing similar functions but with different operation conditions.

Some of the concepts considered for model development are shown in Figure 3. The most extreme concept (concept *a*) uses the "fuse/divide" principle to permanently change the airfoil shape by expelling a larger shell from a smaller airfoil. Concept *b* uses "expose/cover" and "nesting" to create a longer, thinner airfoil by extending an actuator. The "expand/collapse" principle is also used in concept *c* with the "material flexibility" facilitator where a flexible airfoil skin surface is deformed into different shapes by internal actuators. Concept *d* uses the "expand/collapse" principle with the "flip" facilitator. It is recognized that this concept would likely move through an unstable state, as the airfoil is allowed to flip open and it would also be extremely difficult to flip back during flight. Finally, concept *e* uses the "expand/collapse" principle with the "roll/wrap/coil" facilitator to unroll an airfoil skin as different actuators are used. The advantage of this design over the third concept shown is that the perimeter of the airfoil cross-section can handle more extreme changes.

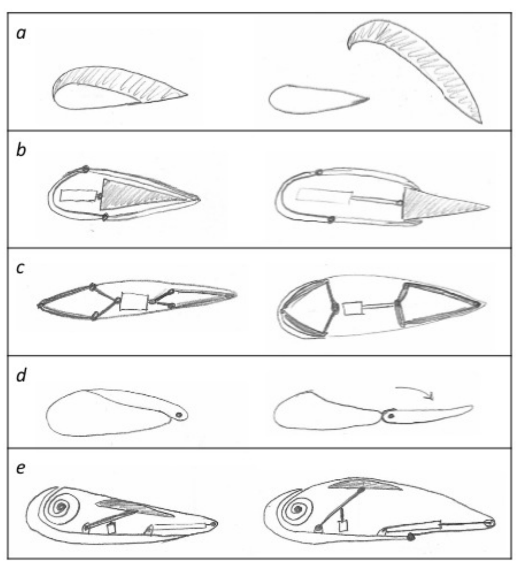


Figure 3. Changeable airfoil concepts

The concepts shown in Figure 3 can be used to determine the way in which design variables are allowed to change during reconfigurable design optimization. For example, concept *a* offers the least restriction on the design variables between the two states. However, the variables can only be changed once during the optimization and must reflect a decrease in airfoil size.

5. MODEL DEVELOPMENT

Computationally optimizing the performance of an unmanned aerial vehicle requires a means of evaluating possible aircraft designs. Previous efforts in the design of a morphing commuter aircraft have used the aircraft sizing code "FLOPS" (Flight Optimization System) [22], developed by NASA's Langley Research Center, to provide an estimate of aircraft size and performance for a given mission description. In this paper, the authors have used seminal works [23-25] in preliminary aircraft sizing to begin the development of a multidisciplinary UAV model. For the purpose of this paper, general aircraft specifications have been established that parallel those of existing multi-mission UAVs, such as the MQ-9 Reaper (Predator B variant). Generalized specifications for the UAV model are listed in Table 1.

Table 1. Generalized specifications for the UAV model

Dimensions	
Wingspan:	66 ft
Length:	36 ft
Fuselage diameter:	3.7 ft
Chord length:	4 ft
Weights	
Empty weight:	5700 lbs
Fuel capacity:	4000 lbs
External payload:	1200 lbs
Performance characteristics	
Engine horsepower:	950 bhp
Specific fuel consumption:	0.4 cruise
	0.5 loiter
Propeller efficiency:	0.8 climb
	0.82 cruise
	0.77 loiter
Performance constraints:	
Maximum takeoff distance:	2300 ft
Minimum rate of climb:	1680 ft/min

5.1 PERFORMANCE PARAMETERS AND MISSION CONSTRAINTS

Multi-mission UAVs, by nature, are expected to provide a wide variety of capabilities. The requirements associated with these capabilities typically conflict, requiring performance tradeoffs to be accepted in the interest of a feasible design. Figure 4 depicts a hypothetical baseline search mission that can be used to quantify the performance of a UAV design.

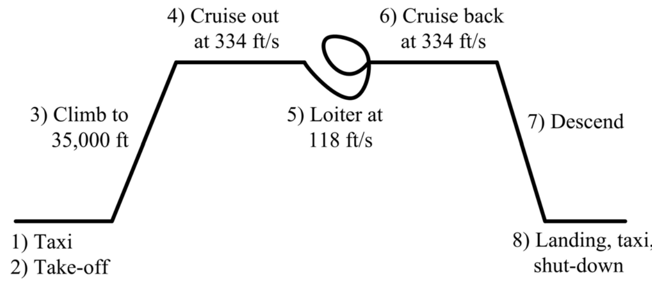


Figure 4. Basic search mission

The mission segments analyzed in this work relate to performance during takeoff, climb, cruise, and loiter. The performance for each of these mission segments is given in Equations (1) – (5):

Takeoff distance [25]

$$s = \frac{1.44W^2}{g\rho SC_{L,\max}\{T - D + \mu_r(W - L)\}} \tag{1}$$

Rate of climb [25]

$$R/C = \frac{TV - DV}{W} \tag{2}$$

Climb phase [24]

$$E_{CL} = 375\left(\frac{1}{V_{CL}}\right)\left(\frac{\eta_p}{c_p}\right)_{CL}\left(\frac{L}{D}\right)_{CL}\ln\left(\frac{W_{i+1}}{W_i}\right) \tag{3}$$

Cruise phase [24]

$$R_{CR} = 375\left(\frac{\eta_p}{c_p}\right)_{CR}\left(\frac{L}{D}\right)_{CR}\ln\left(\frac{W_{i+1}}{W_i}\right) \tag{4}$$

Loiter phase [24]

$$E_{LTR} = 375\left(\frac{1}{V_{LTR}}\right)\left(\frac{\eta_p}{c_p}\right)_{LTR}\left(\frac{L}{D}\right)_{LTR}\ln\left(\frac{W_{i+1}}{W_i}\right) \tag{5}$$

It is apparent from Equations (1) – (5) that the lift and drag forces must be calculated when quantifying the performance of the aircraft during the different phases of the mission. While many computer-based applications, such as XFoil [26], can be used to determine the lifting forces on the aircraft, quantifying the drag force requires the addition of induced drag components. The coefficient of drag for the aircraft when these induced drag components are included is given by Equation (6). Here, C_d represents the drag coefficient of the airfoil. The second term in Equation (6) represents the induced drag coefficient for the *m* components – fuselage and ordnances - that comprise the aircraft. C_{df} value for these various components are given in Table 2. Finally, the last term in Equation (6) accounts for the induced drag of the airfoil.

$$C_D = C_d + \sum_{i=1}^{m} \frac{C_{df} S_f}{S} + \frac{C_L^2}{\pi e AR} \quad (6)$$

Table 2. Induced drag coefficient for various components

Component	C_{df}
Fuselage	0.11
Large external ordnance	0.07
Small external ordnance	0.04

In additional to performance parameters, three constraints must be considered when evaluating a potential UAV design. Equation (1) can be used to ensure that the maximum takeoff distance does not exceed the desired distance. Evaluating Equation (2) ensures that the UAV design meets a minimum rate of climb. The third constraint is established to guarantee that the mission can be completed within the fuel capacity of the aircraft.

Quantifying the UAV's fuel consumption for a specified mission is completed using the mission fuel-fraction approach [24]. This approach breaks the aircraft's mission into specified segments and determines the fuel used during each phase. The fuel used in each segment is determined from calculations or estimated from historical results / experience. For instance, the mission phases associated with warming-up the plane and taxiing have a defined mission fuel fraction of 0.990 based off of historical measurements. Conversely, the mission fuel fraction associated with a cruise phase is dependent on cruise range, fuel consumption ratio, propeller efficiency, and the lift-to-drag ratio, as shown in Equation (4). After the fuel-fractions associated with the *n* phases of the mission have been determined, the fuel consumed during a mission is determined from Equations (7) and (8):

$$M_{ff} = \frac{W_1}{W_{TO}} \prod_{i=1}^{n} \frac{W_{i+1}}{W_i} \quad (7)$$

$$W_{F_{used}} = (1 - M_{ff}) W_{TO} \quad (8)$$

The equations listed in this section provide the detail necessary to quantify the performance parameters for a UAV design and to determine if any mission constraints are violated. The next section of the paper explores the design variables that are used in this problem.

5.2 AIRFOIL DESIGN VARIABLES

As mentioned in Section 4, the focus of this paper is on the subsystem that controls the geometric shape of the UAV's airfoil. The shape of an airfoil can be described by a series of four digits that allow the cross-section of the airfoil to be generated so that the lift and drag properties can be calculated. Nomenclature of an airfoil cross-section is shown in Figure 5.

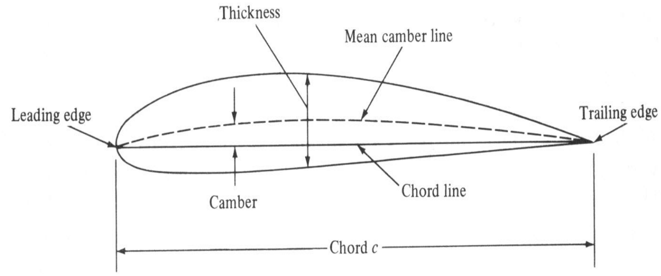


Figure 5. Airfoil nomenclature [25]

For the case study in this work, three design variables are considered from the NACA airfoil. These variables are detailed in Figure 6, where index *i* corresponds to the airfoil created for a specific missions phase.

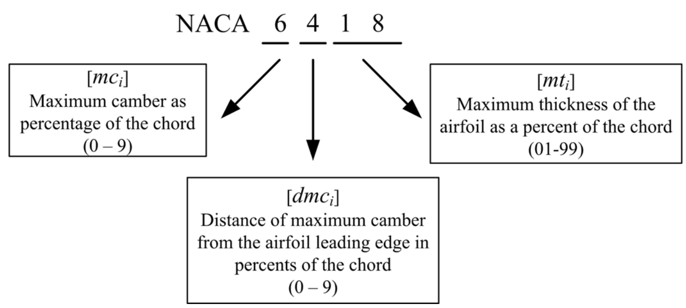


Figure 6. Design variable description

The first two numbers in NACA airfoil 6418 define an airfoil with a maximum camber of 6 percent the chord length, occurring at a distance 40 percent from the leading edge. The last two digits indicate that the maximum thickness of the airfoil is 18 percent the overall chord length of the wing. Changing the values of the NACA number changes the geometric properties of the airfoil, creating a corresponding change in lift and drag properties. From this example, it can also be seen that the values for the three design variables are discrete. Given this discrete nature, a genetic algorithm (GA) is used to optimize the performance of the aircraft for the desired mission.

Airfoil analysis is completed using XFoil [26], allowing for the extraction of lift and drag characteristics at various velocities and with active flap configurations. In this work, 20^o flaps are deployed on takeoff, while the airfoils are analyzed in viscous flow at Reynolds numbers on the order of 10^5 and 10^6. A simulation of airfoil characteristics is conducted with XFoil for each major mission segment, as the speed of the aircraft changes thereby varying the lift and drag properties.

5.3 MISSION DEVELOPMENT

After defining the performance parameters, constraints, and design variables of the problem in the previous two sections, attention can now be turned to mission development. Building upon Figure 4, presented in Section 5.1, a hypothetical baseline mission can be created that examines the performance of a UAV design. The missions created for this profile can be established in the form of a standard optimization problem statement, as shown in Figure 7. This optimization problem statement establishes inequality constraints for the amount of fuel used, the maximum takeoff distance allowed, and a minimum climb rate, and ensures that the aircraft can remain airborne by producing enough thrust and lift to counter the drag and weight forces. These constraints are incorporated into the objective value using a penalty function. Additionally, bounds are placed on the thickness of an airfoil as a percent of the chord length to prevent the airfoil from becoming "too thin" or "too thick".

Objective Functions
Min: fuel
Max: combat radius (cruise distance)
Max: loiter (endurance) time

Design Variables
mc_i, dmc_i, mt_i

Constraints

$W_F < 4000$ lbs	(fuel used constraint)
$s < 2300$ ft	(takeoff distance constraint)
$R/C > 28$ ft/s	(rate of climb constraint)

Available "power" > 0 lbs for each mission segment
5% chord length $\leq$ max thickness $\leq$ 18% chord length

Base mission settings

Combat radius (cruise distance):	1800 miles
Loiter (endurance) time:	35 hours

Figure 7. Formalized optimization problem statement

Depending on the mission aspects considered, multiple forms of the objective function can be constructed. Individual criteria can be considered separately, or multiple criteria can be combined using a weighted-sum objective function. However, when not solely minimizing fuel, an additional sub-optimization is required. When the endurance time or cruise distance for the mission stages are defined for Equations (3) – (5), the result is the weight of the aircraft at the end of the segment. This result is dependent upon the initial weight at each segment, which ultimately is a function of the aircraft's empty weight and the weight of fuel remaining. Therefore, modifying the amount of fuel at takeoff provides different performance characteristics, yielding a single-variable, unconstrained optimization problem. A golden-section approach is used to determine the optimal fuel weight at takeoff to optimize the mission objective function.

Complexity can be added to the mission by including the requirement of external ordnance, as shown in Figure 8. Here, the aircraft is required to launch/drop 1000 lb of external ordnance (e.g. 2 – 500 lb bombs) at the end of the cruise phase. The UAV then loiters at this position, launching/firing 200 lbs of external ordnance (e.g. 2 – 100 lb missiles) before cruising back to base. This requirement of additional ordnance adds an additional 1200 lbs to the aircraft's takeoff weight.

Formalizing the optimization problem statement and the basic mission profile allows for the performance of the aircraft to be compared and contrasted. The three aircraft studied in this investigation are presented in the next section.

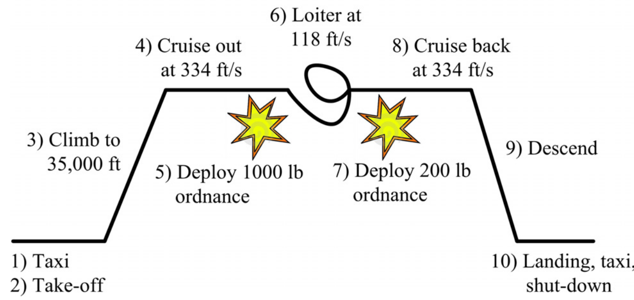


Figure 8. Basic search-and-destroy mission

5.4 SUBSYSTEM CONFIGURATION CHANGES

As part of this investigation, three different UAVs will be considered. The first UAV will be a static aircraft that is incapable of changing its configuration after deployment. This aircraft strictly follows the form of the optimization problem statement in Figure 7, where the index *i* is limited to one.

The second aircraft is an irreversibly changeable system, based on concept *a* in Figure 3. Concept *a* uses the "fuse/divide" principle and "nesting" facilitator to permanently transform the airfoil shape by expelling a larger shell from a smaller airfoil. *It is important to note that while the system can change its configuration in flight, this is a one-time configuration change.* This differs from a proper reconfigurable system that undergoes repeatable, reversible changes. The design variables for this aircraft are the:

- initial (larger) airfoil profile (mc_1, dmc_1, mt_1),
- final (smaller) airfoil profile (mc_2, dmc_2, mt_2),
- mission segment for transition occurrence (x).

Furthermore, an additional constraint is required to ensure that the initial airfoil is thicker than the final airfoil.

- thickness $NACA_1$ > thickness $NACA_2$

The final aircraft considered is a reconfigurable system that uses the "expand/collapse" principle with the "material flexibility" facilitator. In this scenario, a flexible airfoil skin surface is deformed into different shapes by internal actuators. An example of this reconfiguration is demonstrated in concept *c* of Figure 3. In this study, this system is capable of achieving all possible NACA profiles repeatedly and reversibly. The design variables associated with this aircraft are the:

- takeoff stage airfoil profile (mc_1, dmc_1, mt_1),
- climb stage airfoil profile (mc_2, dmc_2, mt_2),
- first cruise stage airfoil profile (mc_3, dmc_3, mt_3),
- endurance stage airfoil profile (mc_4, dmc_4, mt_4),
- second cruise stage airfoil profile (mc_5, dmc_5, mt_5).

Having established the missions, performance parameters, and identifying the possible configuration changes for each aircraft, the next section of this paper compares the advantages of incorporating different transformation principles.

6. RESULTS

In this section, the performance and optimal configuration of three different aircraft are presented. The first aircraft ('*Static*') remains in a fixed configuration after deployment. A second aircraft ('*Irreversible*) is designed using the "fuse/divide" transformation principle and the "nesting" facilitator. Given the nature of this transformation, the change in physical configuration is allowed to occur once during a mission. The final aircraft ('*Reversible*') uses the "expand/collapse" transformation principle and is aided by the "material flexibility" facilitator. This system is allowed repeatable and reversible configuration changes that can occur at each segment of the mission.

6.1 BASIC SEARCH MISSION

As part of this study, three different objective functions are considered separately for each mission: minimize fuel used, maximize combat radius, and maximize loiter time. In future work, other missions can be created that use a weighted-sum approach of these three objectives. Adopting different weighting schemes will change the significance of different mission segments, yielding different optimal results and required reconfigurations. For this mission, the takeoff weight of the UAV is solely empty weight and the required fuel. The results for each objective function are shown below:

Table 3. Minimum fuel results

Aircraft	Fuel used (lbs)	Perf. adv.	Minimum number of possible configurations better than static system
Static	2627	-	-
Irreversible	2414	8.1%	7 optimal, 28 additional
Reversible	**2353**	**10.4%**	1 optimal, 147 additional

Table 4. Maximize combat radius results

Aircraft	Max. radius (miles)	Perf. adv.	Minimum number of possible configurations better than static system
Static	2242	-	-
Irreversible	3505	56.3%	1 optimal, 7 additional
Reversible	**3700**	**65.0%**	1 optimal, 47 additional

Table 5. Maximize loiter results

Aircraft	Max. loiter. (hrs)	Perf. adv.	Minimum number of possible configurations better than static system
Static	42.4	-	-
Irreversible	62.1	46.5%	1 optimal, 26 additional
Reversible	**63.3**	**49.3%**	1 optimal, 153 additional

Both missions in this paper are solved using a genetic algorithm with the following characteristics:

- Population size: 10*number of design variables
- Encoding: real-value
- Crossover type: single-point crossover
- Crossover rate: 80%
- Mutation type: single-value mutation
- Mutation rate: 1%
- Convergence: 25 generations or fixed population fitness average

Additionally, the GA was run multiple times with a unique initial population to ensure that the optimal result was obtained.

The results presented in Tables 3-5 show that, regardless of the performance objective considered, utilizing transformational principles and facilitators in system design yields significant performance increases. Additionally, using these principles presents designers with multiple unique airfoil configuration combinations that perform better than a single, static airfoil. For example, in Table 5 the *Irreversible* aircraft has 27 unique airfoil combinations that perform better than the static system. One of these results is the optimal changeable configuration for this mission / objective function combination. However, there are 26 additional designs that can be selected which perform worse than the optimal changeable configuration but perform better than the static system.

Investigating the result from Table 3, an optimal result for minimizing the fuel used for the *Irreversible* UAV is given by:

- Initial airfoil configuration: NACA 5612
- Final airfoil configuration: NACA 4605
- Transition point: climb phase (step 3)

The initial airfoil configuration (NACA 5612) for this system is identical to the optimal result of the static aircraft. A graphical depiction of these airfoil configurations is shown in Figure 9. Note that in this airfoil depiction, the figure is not to scale, and the x-axis is five times larger than the y-axis. This will be common for all airfoil figures in this paper. The solid line represents the initial airfoil configuration for the UAV. When the aircraft reaches the climb phase of the mission, this airfoil is discarded, leaving the final airfoil configuration, given by the dashed line. This one time configuration change reduces the required amount of fuel by 213 lbs, or 8.1% of the fuel weight.

The *Irreversible* UAV provides a unique result for the minimum fuel scenario - there exist seven unique airfoil combinations that require 2414 lbs of fuel to complete the mission. An analysis of these optimal solutions shows that the final airfoil configurations identified belong to the NACA 460x family of airfoils. Also, significantly more variability was found in the NACA number associated with the initial airfoil configuration.

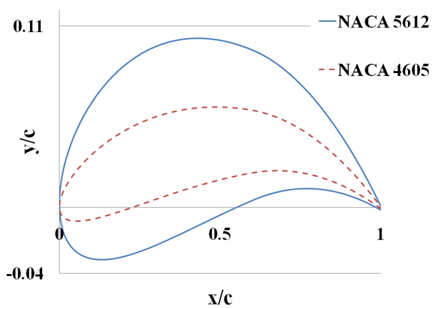


Figure 9. Initial and final normalized airfoil configurations for the *Irreversible* UAV

Given the nature of the transformation principle and facilitator selected, the *Reversible* UAV is designed to undergo repeatable, reversible changes. Therefore, this design is capable of achieving five unique airfoil configurations, corresponding to the mission analysis at takeoff, climb, the two cruise phases, and loiter. Unique to this scenario is the fact that the strengths of certain airfoils can be identified for the different mission segments. For example, the NACA 370x family of airfoils is desired for cruise phases of the mission, while the NACA 560x and 570x families of airfoils are used to maximize endurance. The NACA profiles for the *Reversible* UAV are:

- Takeoff airfoil: NACA 9511
- Climb airfoil: NACA 2808
- Cruise out airfoil: NACA 3706
- Loiter airfoil: NACA 5606
- Cruise return airfoil: NACA 3705

A graphical depiction of these airfoil configurations is shown in Figure 10. The solid line represents the current airfoil configuration for the UAV. The system transitions to the new desired airfoil configuration are given by the dashed line.

Tables 6 and 7 list the optimal configuration, transitions, and transition locations for the three aircraft when maximizing combat radius and loiter time, respectively.

The results of this case study demonstrate the effectiveness of incorporating irreversible and reversible configuration changes into a system. It should be noted that for this study, the properties of the actuators used, and the associated weight increase, in the *Reversible* UAV are not included in the optimization model. The integration of component properties within an optimization framework is a challenging research question outside of this stage-gate analysis, and is addressed in the future work section. Next, the performance of the three aircraft in a search-and-destroy mission scenario is investigated.

Table 6. Results for maximizing combat radius

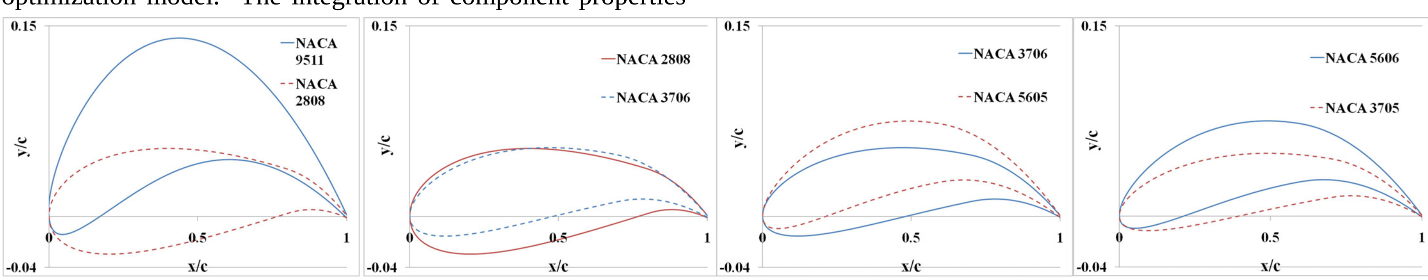
Static UAV	
Airfoil configuration:	NACA 5607
Irreversible UAV	
Initial airfoil configuration:	NACA 9312
Final airfoil configuration:	NACA 4705
Transition location:	climb phase (step 3)
Reversible UAV	
Takeoff airfoil:	NACA 9312
Climb airfoil:	NACA 5505
Cruise out airfoil:	NACA 3706
Loiter airfoil:	NACA 5605
Cruise return airfoil:	NACA 3705

Table 7. Results for maximizing loiter time

Static UAV	
Airfoil configuration:	NACA 6314
Irreversible UAV	
Initial airfoil configuration:	NACA 9314
Final airfoil configuration:	NACA 5605
Transition location:	cruise out phase (step 4)
Reversible UAV	
Takeoff airfoil:	NACA 9313
Climb airfoil:	NACA 5613
Cruise out airfoil:	NACA 3407
Loiter airfoil:	NACA 5705
Cruise return airfoil:	NACA 3706

6.2 BASIC SEARCH-AND-DESTROY MISSION

For the purpose of this investigation, the three UAV scenarios (Static, *Irreversible*, and *Reversible*) are outfitted with a payload of 1200 lbs, and their performance is analyzed with respect to the same three objective functions considered in the previous section. When minimizing the fuel to complete the mission, initial results from the genetic algorithm found that no feasible solution could be developed for any of the UAV scenarios. An investigation of the active constraints identified the takeoff distance constraint ($s < 2300\ ft$) was being violated



Takeoff - Climb | Climb – Cruise out | Cruise out - Loiter | Loiter – Cruise back

Figure 10: Reconfigurations of *Reversible* UAV for baseline search mission

for all designs considered. As the weight of the UAV was increased by over 30% of the empty weight, the takeoff constraint was relaxed so the UAV could use 3000 ft of runway.

Relaxation of the takeoff constraint permits feasible designs for the *Irreversible* and *Reversible* UAV, as shown in Table 8. However, even with the relaxed takeoff constraint, no static design was found which satisfied the constraints originally developed in Figure 7. Further analysis of the problem discovered that the increase in payload, coupled with the original mission constraints, requires a minimum takeoff distance of over 5000 ft for a static UAV. This yields a significant conclusion: changing the configuration after deployment allows for feasible designs to be identified even when static configuration feasible designs cannot be found.

Table 8. Minimum fuel for search-and-destroy mission

Static UAV	
Airfoil configuration:	none feasible
Irreversible UAV	
Minimum fuel required:	2857 lbs
Initial airfoil configuration:	NACA 8210
Final airfoil configuration:	NACA 4605
Transition location:	climb phase (step 3)
Reversible UAV	
Minimum fuel required:	**2817 lbs**
Takeoff airfoil:	NACA 8317
Climb airfoil:	NACA 5410
Cruise out airfoil:	NACA 4605
Loiter airfoil:	NACA 5606
Cruise return airfoil:	NACA 3705

Tables 9 and 10 list the optimal configuration, transitions, and transition locations for the two aircraft when maximizing combat radius and loiter time, respectively. From the results of these three studies, it is apparent that the additional payload weight requires the maximum camber to be around the top feasible values for takeoff.

Table 9. Max. combat radius for search-and-destroy

Static UAV	
Airfoil configuration:	none feasible
Irreversible UAV	
Maximum combat radius:	2074 miles
Initial airfoil configuration:	NACA 9312
Final airfoil configuration:	NACA 4605
Transition location:	climb phase (step 3)
Reversible UAV	
Maximum combat radius:	**3690 miles**
Takeoff airfoil:	NACA 9311
Climb airfoil:	NACA 3809
Cruise out airfoil:	NACA 3705
Loiter airfoil:	NACA 6505
Cruise return airfoil:	NACA 4505

Additionally, these results show that once the plane is airborne, a thicker airfoil is desired when climbing than for the remaining phases of the mission. Finally, similar airfoil shapes are desired for the cruise and loiter phases of this mission as were selected for the basic search mission.

Table 10. Maximum loiter for search-and-destroy mission

Static UAV	
Airfoil configuration:	none feasible
Irreversible UAV	
Maximum loiter:	38.8 hours
Initial airfoil configuration:	NACA 9314
Final airfoil configuration:	NACA 4606
Transition location:	climb phase (step 3)
Reversible UAV	
Maximum loiter:	**53.7 hours**
Takeoff airfoil:	NACA 9313
Climb airfoil:	NACA 5118
Cruise out airfoil:	NACA 4505
Loiter airfoil:	NACA 6507
Cruise return airfoil:	NACA 4608

7. CONCLUSIONS AND FUTURE WORK

The results of both missions demonstrate that changeable airfoils have a significant performance advantage over a static, non-changing airfoil. Further, the data supports that the *Reversible* UAV outperforms the *Irreversible* UAV. This result should be expected, as the *Reversible* UAV is capable of constantly tuning its performance to meet the demands of changing mission segments. However, performance alone should not be considered when selecting the transformation principle to integrate into the system. Other parameters such as cost, power requirements, complexity, and technological availability must also be considered when making this decision. However, these criteria are not considered during this stage-gate procedure and need to be integrated into the development of the multidisciplinary optimization problem model.

What this work demonstrates is the power of incorporating transformation principles and facilitators when designing a changeable system. As shown in the previous section, such systems are capable of significant performance advantages over static systems. Furthermore, as seen in the search-and-destroy mission, the incorporation of configuration changes permit feasible designs to be developed when none can be found for a static system. This capability has potential applications in increasing a system's life-span as changes occur within the operating environment and to mission objectives / expectations.

A source of future work is integrating component properties into the optimization framework. For this step to occur, the physical embodiment of the solution principle needs to be determined. A subset of properties from different technological solutions includes the range of motion, number of active axes, step size, maximum speed, etc. If actuators are chosen as the means to achieve a desired transformation principle, these properties will serve to constrain the allowable design variable changes in a reconfigurable system, properly reflecting the attainable range of change and performance.

Finally, another area of future work is building upon the model presented in this paper by integrating additional subsystems to form a complete, realistic model for a reconfigurable UAV. Here, the transformations studied focus solely on the analysis of the UAV's airfoil, achieving a significant performance advantage over a static system. As additional subsystems are added to this model, as shown in Figure 11, the performance advantages of potential transformations must be modeled and quantified. Additionally, the interactions between these subsystems must be studied, as a reconfiguration within one discipline may have an impact on the performance of other subsystems. Care must be taken to avoid negative impacts, while determining which transformation principles and facilitators allow reconfigurations that attain the greatest increases in performance.

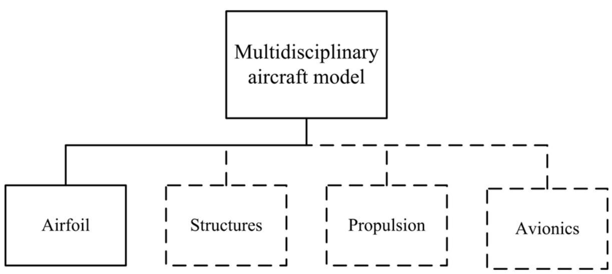


Figure 11. Future subsystems for the multidisciplinary aircraft model

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REFERENCES

[1] Olewnik, A., Brauen, T., Ferguson, S., and Lewis, K., 2004, "A Framework For Flexible Systems And Its Implementation In Multiattribute Decision Making," *ASME Journal of Mechanical Design*, 126(3): 412-419.

[2] Siddiqi, A., de Weck, O. L., and Iagnemma, K., 2006, "Reconfigurability in Planetary Surface Vehicles: Modeling Approaches and Case Study," *Journal of the British Interplanetary Society*, 59.

[3] Ferguson, S., Lewis, K., de Weck, O., and Siddiqi, A., 2007, "Flexible and Reconfigurable Systems: Nomenclature and Review," *2007 ASME DETC and CIE Conferences*, Las Vegas, NV, DETC2007/DAC-35745.

[4] Park GJ, 2007, Analytic Methods in Design Practice, Springer, Germany.

[5] Flanagan, R., Strutzenberg, R., M., and Rodrian, J., 2007, "Development and Flight Testing of a Morphing Aircraft, the NextGen MFX-1," *48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, Honolulu, HI, AIAA-2007-1707.

[6] Gal-Rom, Y., and Raveh, D., 2008, "A Simplified Aero-Structural Model for Inflated Wings," *49th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, Schaumburg, IL, AIAA-2008-1902.

[7] Bubert, E., Woods, B., Kothera, C., Wereley, N., 2008, "Design and Fabrication of a Passive 1-D Morphing Skin," *49th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, Schaumburg, IL, AIAA-2008-2045.

[8] Andersen, G., Cowan, D., and Piatak, D., 2007, "Aeroelastic Modeling, Analysis and Testing of a Morphing Wing Structure," *48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, Honolulu, HI, AIAA-2007-1734.

[9] Olewnik, A., and Lewis, K., 2006, "A Decision Support Framework for Flexible System Design," *Journal of Engineering Design*, **17**(1): 75-97.

[10] Khire, R., and Messac, A., 2008, "Selection-Integrated Optimization (SIO) Methodology for Optimal Design of Adaptive Systems," *Journal of Mechanical Design*, **130**(10): 101401.

[11] Martin, E., and Crossley, W., 2002, "Multiobjective Aircraft Design to Investigate Potential Geometric Morphing Features," *AIAA's Aircraft Technology, Integration, and Operations (ATIO)*, Los Angeles, CA, AIAA-2002-5859.

[12] Roth, B., and Crossley, W., 2003, "Application of Optimization Techniques in the Conceptual Design of Morphing Aircraft," *3rd AIAA ATIO Forum*, Denver, CO, AIAA-2003-6733.

[13] Ferguson, S., and Lewis, K., 2008, "Investigating the Interaction between Reconfigurability and System Mass using Multidisciplinary Design Optimization," *49th AIAA/ASME/ASCE/AHS/ACE Structures, Structural Dynamics, and Materials Conference*, Schaumburg, IL, AIAA-2008-1803.

[14] Ferguson, S., and Lewis, K., 2006, "Effective Development of Reconfigurable Systems Using Linear State-Feedback Control," *AIAA Journal*, **44**(4): 868-878.

[15] Siddiqi, A., and de Weck, O. L., 2008, "Modeling Methods and Conceptual Design Principles for Reconfigurable Systems," *Journal of Mechanical Design*, **130**(10): 101102.

[16] Chmarra, M. K., Arts, L., and Tomiyama, T., 2008, "Towards Adaptable Architecture," *ASME International Design Engineering Technical Conference and Computers and Information in Engineering Conference*, New York, NY, DETC2008-49971.

[17] Arts, L., Chmarra, M. K., and Tomiyama, T., 2008, "Modularization Method for Adaptable Products," *ASME*

International Design Engineering Technical Conference and Computers and Information in Engineering Conference, New York, NY, DETC2008-49338.

[18] Hazelrigg, G. A., 1998, “A Framework for Decision-Based Engineering Design,” *ASME Journal of Mechanical Design*, **120**: 653-658.

[19] Skiles, S. M., Singh, V., Krager J., Wood, K., Jensen, D., and Szmerekovsky, A., 2006, “Adapted Concept Generation and Computation Techniques for the Application of a Transformer Design Theory,” *ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, Philadelphia, PA, DETC2006-99584.

[20] Singh, V., Skiles, S. M., Krager, J., Wood, K., Jensen, D., and Szmerekovsky, A., 2006, “Innovations in Design through Transformation: A Fundamental Study of tRaNsFoRmAtIoN Principles,” *ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, Philadelphia, PA, DETC2006-99575.

[21] Singh, V., Walther, B., Koraishy, B., Krager, J., Wood, K. L., Putnam, N., and Jensen, D., 2007, “Design for Transformation: Theory, Method and Application,” *ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, Las Vegas, NV, DETC2007-34876.

[22] McCuller, L. A., 1998, “FLOPS Flight Optimization System Release 5.94 User’s Guide,” NYMA, Inc., NASA Langley Research Center, Hampton, VA.

[23] Raymer, D., 1992, Aircraft Design: A Conceptual Approach, American Institute of Aeronautics and Astronautics, Inc., Washington, D.C.

[24] Roskam, J., 1997, Airplane Design, Part I: Preliminary Sizing of Airplanes, Design, Analysis and Research Corporation, Lawrence, Kansas.

[25] Anderson, J.D., 1989, Introduction to Flight, 3rd edition, McGraw-Hill, Inc., New York.

[26] Drela, M., 1989, “XFOIL: An Analysis and Design System for Low Reynolds Number Airfoils”, *Low Reynolds Number Aerodynamics*, **54** Springer-Verlag Lecture Notes in Engineering.

APPENDIX A – TRANSFORMATION PRINCIPLES AND FACILITATORS

Principles	Expand/Collapse	Change physical dimensions of object along and axis, in a plane, or in three dimensional space
	Expose/Cover	Expose/Cover a new surface to alter functionality
	Fuse/Divide	Make single functional device become two or more devices, at least one of which has its own distinct functionality defined by the state of the transformer or vice versa
Facilitators	Common core structure	Compose devices with a core structure that remains the same, while the periphery reconfigures to alter the function of the device
	Composite	Form a single part from two or more parts with distinct functionality
	Conform with Structural Interfaces	Statically or dynamically constrain the motion of a component using structural interfaces
	Enclosure	Manipulate object in two or three dimensions in order to enclose a three dimensional space
	Flip	Perform separate functions based on orientation of the object
	Function Sharing	Perform two or more discrete functions
	Furcation	Change between two or more discrete stable states determined by boundary conditions
	Generic Connections	Employ internal or external connections (structural, power) that can be used by different modules to perform different functions or perform the same function in a different way
	Interchangeable transmissions	Use multiple transmissions to produce different motions
	Material Flexibility	Change object dimensions with change in boundary conditions
	Modularity	Localize related functions utilizing common signal, material, and force flows into subsystems (modules) which are easily integrated into the device and may be interchangeable
	Nesting	Place an object inside another object wholly or partially wherein the internal geometry of the containing object is similar to the external geometry of the contained object
	Segmentation	Divide single contiguous part into two or more parts
	Shared Power Transmission	Transmit power from a common source to perform different functions in different configurations
	Shelling	Embed functional element in a device which performs a different function

Figure A1. Transformation design principles and facilitators