

**Incorporating Flexibility into System Design:
a novel framework and illustrated developments**

by

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Submitted to the Department of Aeronautics and Astronautics
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Abstract

Many complex engineering systems in general, and aerospace systems in particular, are highly "optimized" designs, fielded to provide mission superiority or market competitive advantage. Two noticeable trends over the last few decades in engineering design have been increased optimization of the system architecture (mission-specific systems), and increased system design lifetime or service life. Unfortunately, many complex engineering systems often outlive the mission they were designed to address or the market they were designed to service (the mission being no longer relevant in the new environment or context, or in the case of a commercial system, the market has evolved beyond the need for that particular service). Because such complex engineering systems were initially highly optimized for that specific mission or market, they are often unable to modify their capabilities in order to address the new missions or markets that arise with time.

In this thesis, we develop a framework that allows a system to be designed to maintain the competitive advantage despite environmental change. The resulting flexible system can refocus its core capabilities to meet new mission requirements. Within the context of this work, refocusing is achieved by exchanging key components needed for the old mission, for those needed in the new mission.

A strategy to increase a system's flexibility was adapted from the art of platforming. A flexible system would enable the customer to exchange the obsolete components used for an old mission, for the components needed for a new mission (termed the frame), at a sufficiently low cost, and sufficiently short downtime. That which is not upgraded, and remains constant through all transitions of mission focus, is termed the platform.

A system has an inherent ability to satisfy the functional requirements of the mission it was designed for, or other missions. This inherent ability is taken as a baseline. Flexibility of the system is then measured as the performance increase (output) corresponding to the required cost and time to realize the change. Presented herein are tools to conduct a cost-benefit analysis for increasing the flexibility of a system.

The developed methodology is then applied to design a mission flexible Unmanned Aerial Vehicle. Matrices to evaluate the costs and benefits of flexibility are further explained in the context of the case study. The results show that the degree of flexibility can be adjusted to trade between the point performance of each mission, and the cost and time required to transition between missions. The case study has been included to help clarify some of the trade offs inherent to increasing flexibility, and to further discuss the tools at hand to quantify the value flexibility.

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M.I.T. is a place where giants walk amongst men. I have been fortunate to know a few, and they have shaped my life.

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Chapter 1

Introduction

1.1 Motivation and The Prior Art

Over a long enough time scale, all systems become functionally obsolete¹. They may wear out through use, they may fail prematurely², or the functionality they enable may cease to be useful. This work seeks to provide a framework with which to curtail the final slip into obsolescence.

Flexibility has been described as the ability of a system to maintain the competitive advantage despite environmental change. The precursor to this work [12] noted that some biological systems are flexible to respond to environmental change, while others are rigid and die out. To determine the difference, we examine the adaptation of biological systems for both insight and inspiration. The first observation looks at the possession of favorable traits that enable survival. Man has learned to create systems, aided through the development of optimization techniques, that possess many favorable traits to excel in a pre-determined operation, or mission. These systems, termed Optimal Point Designs (OPD), are the benchmark for performance at their intended mission. The question of flexibility looks to assess how such a system will fair through environment change, and hence, mission change.

In his work, Saleh [12] points out numerous examples, from satellite constellations

¹With the potential notable exception of the creations from Antonio Stradivari

²Premature component failure is known as infant mortality, and is reduced through ‘burn in’

to supersonic bombers, that were designed as OPDs, and retired well before the expiration of their intended service lifetime. Retirement can be attributed to the inability of said systems to meet changing mission requirements. Returning to nature, we find solutions that have weathered many a storm.

1.1.1 Adaptation and Evolution

Adaptation is viewed, within the context of this work, as the ability of an individual system (biological or man-made) to meet new requirements that arise in its lifetime. The individual has an ability, perhaps a previously unused ability, that becomes useful to combat pressures that arise in time.

Evolution, on the other hand, occurs through the reproductive spread of this ability, such that many systems within the species gain the ability to adapt, and the whole species evolves. Man-made products evolve with a similar dissemination of favorable traits. Of course, they are designed into new models, not passed genetically.

The evolution of a man-made product line is seen in the successive release of enhanced systems. The new system must be procured to gain the benefits, or the advancement, over a currently fielded system. An example of this is the annual car. Adaptation, on the other hand, is the enhancement or change of a fielded system. If such a change has a low cost-benefit ratio, as defined by the customer or market, the system is deemed flexible.

We look now at the change of form, to follow function, as a process of adaptation used in biological systems.

1.1.2 Form Follows Function

In most cases, capabilities require recourses from the system, and form follows function. Consequently, it is difficult, if possible, to design a system innately capable of weathering all storms. One might call that system "jack of all traits, master of none".

Nature has, of course, learned how to endow systems with the ability to adapt within their lifetime. The evidence is omnipresent, and a simple example can be seen

in physical conditioning and muscle constituency. Maintaining muscle mass requires resources from the biological system. To minimize waste, or excess, a muscle unused will atrophy over time. However, a muscle constantly taxed will grow to enable increased performance at the task which is taxing it.

Taking one cut deeper, researchers have shown endurance training of animals may transition their skeletal muscle (from type II to type I) to improve performance at endurance missions [16]. Ultimately, the biological system will reduce, or enhance, a functionality based on the task it needs to perform. Form follows function, and both change with time to meet new, arising, needs. This is the essence of flexibility within the lifetime of a single system.

We seek now, to mimic nature's solution of growing or shrinking capabilities over time to constantly tailor a system to evolving missions. Like nature, we do not claim to spontaneously generate functionality. Rather, we enable a potential, which may or may not be enhanced over time. In some cases, the potential is the inclusion of a mounting bracket or interface. Such an inclusion may yield no inherent functionality at the time of fielding. Instead, it can quickly accommodate the addition of a component or subsystem. At the same time, we allow subsystems in use to shrink, freeing resources for the growth of new abilities. Of course, our engineering systems changes are taken in discrete steps, rather than the continuous change of biological systems.

It is therefore desirable for a complex engineering system to possess the ability to satisfy evolving functional requirements that the customer may have during the entire operational lifetime of the system. However, designing a high-performance system with the ability to address multiple, sometimes competing, needs, defined as missions, could result in an averaging effect³ that reduces the performance of the Multi-Mission Capable (MMC) system below that of individually optimized systems. This reduction in performance, hereby termed the performance gap (between the individually optimized designs and the MMC), can be large enough to preclude the MMC from satisfying the customer's needs for a given mission. In the extreme cases

³This is the concept of 'satisficing' introduced by H. Simon in 1956 as an alternative to optimization.

where mission superiority is essential, the acceptable performance gap can be quite small.

This work focuses on enabling mission flexibility in a system, while reducing the associated performance gap. Instead of including the capability to fulfill every need, the system is designed to meet the current needs with the potential to address a set of predicted needs. Each future need, or mission, will be fulfilled by tailoring the system into a mission-specific derivative of the original system. It will be shown that having only the potential, and not the hardware and software required for each mission, will increase the performance of each mission derivative while including the option to transition to a different mission derivative. A method is proposed to reduce the economic and performance cost of the option to the point that the customer would gain value by including option in the design of a new system. This is the essence of incorporating mission flexibility in the design of a new system.

1.2 Thesis Outline and Contributions

The introduction established the advantage of designing mission flexible systems, and gave an preliminary look at how we seek to achieve such flexibility. The ensuing chapters will discuss: 1) the opposing forces governing the design of flexible systems, 2) an optimization framework to achieve flexible systems, and 3) a case study to design a flexible Unmanned Aerial Vehicle.

Chapter 2 presents a conceptual overview of the opposing forces acting on the design of a flexible, cutting-edge system. We begin with a brief discussion of optimization used as a tool in the design process to increase the performance of one-point designs. Next, we explain how obsolescence- the driver behind the pursuit of flexibility- sets in as systems age. The exposed rigidity, or resistance to change, of Optimal Point Designs (OPD) will motivate the addition of flexibility through the inclusion of capabilities in excess of the original mission needs. Finally, we touch upon the interplay of flexibility and optimization to set the stage for the proposed design cycle.

Chapter 3 develops a systems-level approach for embedding flexibility in the design of a new engineering system, along with the potential performance penalties, and a mitigation strategy adapted from platform design. We start with a simplified engineering systems design cycle. The core of the design cycle optimizes the system's performance of the functional requirements defined for a given mission. Next, flexibility of the system to address additional missions is added to the optimization objective. The resulting decrease in performance, of the flexible system compared to the rigid system, is explained.

An optimization framework is then presented to design flexible systems, and quantify the trade-offs inherent to flexibility. Additional controls are discussed to help the designer tune the optimization based on the preferences set by the customer. The presented methodology is then used to design a flexible Unmanned Aerial Vehicle.

Chapter 4 is a case study that provides a concrete illustration of the proposed flexible design cycle. Moreover, design decisions that are better understood in the context of an example are presented at the end of chapter 4. The case study entails the design of a mission flexible Unmanned Aerial Vehicle, starting with the customer needs, and resulting in flexible platform based UAVs. In the process, we quantify the Performance Gap of adding flexibility and show how the proposed platform approach yields a performance advantage for the fielded systems. The design cycle ends with a set of platform based UAV designs.

The results section of chapter 4 contains a detailed discussion of the time and economic costs in exercising the option to transition from one mission specific system to another. As one might guess, increasing the performance advantage of the platform approach requires a corresponding increase in cost and complexity (time) to transition a system's mission focus. Since the discussion is better understood in the context of the example, and can be presented with no loss of generality, it is included in chapter 4 instead of chapter 3. The core of chapter 4 introduces the measure of flexibility with respect to Performance, Cost, and Time. In time, a system may be forced to address a mission other than the one it was originally designed for. The inherent performance of the fielded system at the new mission is a baseline of performance. The flexibility

of the system is the ratio of performance enhancement (output) to the cost and time required to realize such an enhancement (inputs).

While the focus of this work has been to combat mission obsolescence, the author has included a Three Tiered Architecture to facilitate the upgrade of certain components in the avionics system. In the context of the case study, the proposed strategy will significantly prolong the onset of component obsolescence.

The design of a mission flexible UAV has been formulated as a tractable problem. Specifically, an accurate model was adapted to predict system performance, and known data was used for direct calculation the associated cost and time to transition mission specificity. Indeed, the example is simplified as compared to a full-scale system design. However, throughout chapter 4 we explain how to map the UAV results to full-scale designs across other industries.

Chapter 5 contains the conclusions and recommendations for future work.

1.2.1 Research Contributions

There are two noteworthy contributions from this research. The first, the essence of the work, is the mapping of flexibility achieved in nature to the systems created by man. The explanation of this mapping, and the sufficient teaching for use by others in forthcoming designs, constitutes the primary contribution. Part of this contribution is the quantification of a systems' flexibility such that the effects of increasing flexibility can be assessed. Defining the flexibility of a system as the ratio of performance enhancement (output) to the cost and time required to realize such an enhancement (inputs), enables a concrete discussion of what flexibility entails. The third contribution pertains to the approach the author uses to relate the proposed design principals to an existing art.

The current proposed solution borrows ideas from the art of platforming. Indeed, the commercial benefits of platform design have been widely studied and established from the standpoints of diversity [9], design [11], production [14], inventory [1] and support. In these cases, however, the benefits of introducing a platform are offset by a reduction in performance of the individual platform derivatives [8].

This art is awash with the benefits of platforming. The philosophy is to derive economic benefit through the release of current models, and in future models, at the satisfaction of some level of constraints. Having been involved in a project to design an optimal platform, for use across differing markets, the author appreciates the benefits of such approaches.

A flexible platform, from a platforming standpoint, is typified by the ability of Nissan to build a two seat sports car, and a 4 seat luxury sedan on the same platform. However, if you have a sports car, and family pressure requires you to transition it to a sedan, you must trade it in. Otherwise, the lack of rear seating will prevent the sports car from fulfilling the new family transportation mission.

Interestingly, both the sports car, and the sedan, share many pieces. You are, in fact, trading in the whole system for the exchange of a few pieces (hereby termed the frame) that re-tailor the use from fast, to fast for four. This is an acceptable practice as the market for used sports cars is strong, thus generating a decent trade-in value, and enabling the customer to transition to the sedan.

However, if every auto operator faced such a pressure at the same time, the trade-in value would plummet, and the afore mentioned exchange would not be an option. This is the fate of high-technology systems operated in hyper-competitive environments. Hence, a flexible platform, from the viewpoint of flexibility, would enable you to trade only the obsolete frame, for sufficiently low cost, and sufficiently short downtime. Thus, only the obsolete components are upgraded. That which is not upgraded, it termed the platform.

Chapter 2

Optimization, Obsolescence, and Flexibility

High-performance engineering systems result from intensive mission-specific optimization that pushes the technological forefront. Interestingly, the same high-technology component base and refined optimization that originally enabled mission superiority often drive the system to obsolescence well before the designed lifetime is up [12]. Such systems are retired, along with potential life, in full working condition. Understanding the design process for high performance systems reveals one of the largest obstacles to incorporating flexibility.

This chapter will start with a brief discussion of optimization. The process of optimization can be understood as the tightening of a systems' focus for a specific mission. By focusing the recourses and capabilities of a system on a single mission, the designer is able to maximize the performance of said mission. Accordingly, system capabilities in excess of what the mission requires will likely be pruned during the optimization process. As time progresses, however, the customer may need the system to address other missions, potentially requiring capabilities that were striped away during the optimization process. Having removed the excess capabilities, to enhance the point performance of the system, the system has been made inflexible (rigid) to meet new missions. Rigidity precludes the system from refocusing its capabilities to address missions that arise in time. Accordingly, the systems' performance at these

new missions suffers, rendering the system obsolete.

We seek to overcome the standoff by including the potential to enhance a systems capabilities in excess of the original mission requirements. Including such potentials requires some sacrifice in performance for the flexibility to refocus a system to address new missions that arise in time. Tuning the level of the performance sacrifice, and hence the level of flexibility, will be discussed in chapters 3 and 4. For now, we return to optimization to explain its utility in system design, and the removal of excess.

2.1 Optimization

We start our discussion of optimization with the introduction of efficient algorithms that brought forth performance enhancement in engineering systems. The "simplex method", proposed by Dantzig in 1947, enabled the efficient solution to linear programming problems. Shortly there after, Dantzig published a general simplex method capable of solving linear optimization problems subject to linear inequality constraints [4]. Since then, much research has focused on the effective modeling of linear problems [3], and nonlinear problems [2]. The core concept of optimization is to minimize (or maximize) and objective through feasible perturbation of design variables. In many cases, there are constraints on the design variables and other constraints imposed by the market, manufacturing, or performance, etc.

Such systems are optimized, in a classical sense of the word, by pruning all capabilities that are not necessary to fulfill the currently specified functionalities. Capabilities are everything from the strength of a structure, to the power of an electrical system, to the stall speed of an airfoil. In the context of structures, an optimal fuselage satisfies the mission load requirements ¹, but fails with the slightest increase in load. With a minimally sufficient structure, the vehicle can accelerate faster ($F = ma$), fly further ², climb higher (ceiling). It is the removal of excess that enables mission superiority and defines an optimally efficient design. The theoretical result of such a

¹including Factor of Safety and Margin of Safety

²less lift, less drag and propulsive requirement

process is the optimal system, for a given mission, at the current time. A realizable design will have performance slightly shy of this point, where the magnitude of the difference defines the quality of design.

Multidisciplinary optimization techniques yield demonstrable advantages. The interested reader is referred to [15] and [17] for applications to aerospace problems. The advantages and limitations of multicriteria design of an optimal platform is discussed in detail by [8].

Optimization can be understood as focusing the capabilities of a system on a given mission. Over time, changing customer needs may require the system to refocus its capabilities. If the system does not possess the necessary recourses, or cannot be retrofitted with needed recourses in a cost effective manner, it will fail to meet the new focus and be termed obsolete.

2.2 Obsolescence

The driving forces that result in obsolescence can be partitioned into two categories. The first, mission obsolescence, occurs when the customer needs change beyond the adaptability of the original system [13]. The system does not perform the new mission as well as it performed the original mission it was designed for. Dulling of the competitive edge renders the system obsolete.

The second force eroding a system's performance, as compared to a current state of the art system, is component obsolescence. Assuming the system survives mission obsolescence, the component base that makes up the system will become obsolete as a function of time [7]. One mechanism of component obsolescence is attributed to the advancing technological front, which will eventually dwarf the built in component base of the system. This problem is especially prevalent in areas of rapid technological advancement, such as with integrated circuits. In systems designed for long service lifetimes, however, even the slower progressing parts suffer from obsolescence. As a side effect, replacement parts for the increasingly outdated components become scarce, expensive, and eventually unavailable [10]. While the focus of this work lies

on thwarting mission obsolescence, a Three Tiered Architecture to combat component obsolescence has been provided in the case study.

2.3 Excess Capability

From the previous discussion, it might appear that flexibility and optimization are antagonistic approaches to system design. Indeed, in order to thwart obsolescence (through flexibility), one needs excess capability in a system to satisfy new or additional functional requirements that will arise over the system's lifetime. But this excess capability is not needed at the time when the system is designed or fielded, and will therefore be stripped away if the system is 'optimized' for its current mission (and functional requirements), hence precluding it from being 'flexible'.

2.4 Potential for Excess

In the following chapter we propose to resolve the standoff between optimization and flexibility by including in the system architecture only the potential for excess capability, as opposed to the capability itself. One way to build in these potentials is through a platform and frame approach. The platform can be thought of as a constant through the transition of a single system's mission specificity. The frame, on the other hand, is the summation of additions to the platform that enable a platform based derivative to fulfill a single mission. Some, or all, of the frame pieces are changes when a system transitions mission focus. The exchange of the frame pieces allows the tailoring, to a degree, of each system to single mission.

In essence, the frame pieces are optimized for individual missions, and exchanged through mission transition. The platform, on the other hand, represents a compromise between the considered missions that is capable of accepting the optimal frame pieces for each mission. By partitioning the optimization into mission specific frames, and a common platform, we increase the performance of each mission derivative, while enabling a sufficiently low cost and time to transition mission focus (from one mission

to another) by having a constant platform.

The ensuing chapter will present an optimization framework capable of designing flexible systems and quantify the trade-offs inherent to adding flexibility.

Chapter 3

Adding Flexibility in System Design

3.1 Introduction

Engineering systems design is a well studied art. The complexity of the design process grows rapidly with the addition of considerations beyond performance and cost. Significant work has been devoted to address a variety of pressing issues such as supporting a fielded product [1], or the production advantages of using common parts [14]. In this chapter, and the following case study in chapter 4, the scope is limited to performance, cost, and product assembly time. Herein, we present one approach for designing high performance systems, or Optimal Point Designs (OPD) built to satisfy current customer needs. The process is then modified to satisfy the current needs with the inclusion of mission flexibility to address future needs.

3.2 Optimal Point Designs

A design cycle is proposed to achieve flexible design using multi-objective optimization and platforming. As Eq. 3.1 depicts, a progression is used to define functional requirements based on customer needs. A set of functional requirements is grouped together to define a mission. More than the title of a group, the mission definition

is the statement that defines the mission objective. For example, in the case study, an Unmanned Aerial Vehicles (UAV) is presented that must satisfy the customers needs to Find and Follow Named Areas of Interest (NAIs). This mission, Search and Reconnaissance, has Functional Requirements (FR) of the Range, and Time on Target. Accordingly, these two FR will be maximized in the optimization of the UAV. With a clearly articulated objective, it is easy to predict if an added functional requirement is aligned with the other functional requirements (supportive), or would necessitate a compromise of the other requirements (non-supportive).

$$\begin{aligned}
 \text{Customer Needs} &\Rightarrow \text{Mission Definition} \Rightarrow \dots & (3.1) \\
 & \text{Functional Requirements} \Rightarrow \underbrace{X}_{\text{Design Parameters}}
 \end{aligned}$$

Using the progression of Eq. 3.1, the currently contracted mission M_1 is defined. Next, the functional requirements $FR_{1,n}$, are generated as shown in Table 3.1. For the 1st Optimal Point Design OPD_1 , a combination of these functional requirements is used as the objective function over which the system is evaluated and optimized, Eq. 3.2. As such, any potential abilities that decrease the performance of $FR_{1,n}$'s will be stripped from system. Potential abilities may include the strength of the structure, engine power, computational power, etc. The resulting OPD_1 represents that best possible design for the current time period (level of technology). Accordingly, it is used as a benchmark to measure the ability of others systems to satisfy M_1 , as defined by FR_1 . For example the performance of the Multi-Mission Capable(MMC) system will be gaged against OPD_1 to asses the MMC's performance at M_1 .

$$\text{Objective} = \underbrace{f(FR_{1,n})}_{\text{Optimal Point Design}} + \underbrace{f(FR_{2,m}) + \dots + f(FR_{g,l})}_{\text{FRs Added to Introduce Flexibility}} \quad (3.2)$$

Changing the mission specificity of a system from M_1 to M_2 , by adding FR_2 (the functional requirements that define Mission 2) after the original system has been fielded will likely require expensive re-design. For example, consider a fielded airplane

Mission	Functional Requirements
Contracted, M_1 Current	$FR_{1,1}, FR_{1,2}, \dots FR_{1,n}$
Predicted, M_p Current	$FR_{2,1}, FR_{2,2} \dots FR_{2,m}$
Predicted, Future	$FR_{3,1}, FR_{3,2} \dots FR_{3,l}$

Table 3.1: Current and predicted missions

that needs to carry additional payload on the wings. As we propagate the requirements change through the system, we find that a multitude of design changes are needed. One can think of the system as a Rub Goldberg device. The transformation starts by enhancing the wing box, which then requires new fuselage mounting points, and in turn mandates new tooling and recertification, etc. Eventually, one realizes that the resulting system, aging and slowed down by the carryover of obsolete capabilities, is not worth the expenditure. Therefore, the original system can be retired due to mission obsolescence, or can be used in a highly sub-optimal fashion to carry out M_2 . Had the fielded system been designed with the potential to refocus its capabilities from M_1 to M_2 , the onset of obsolescence would be prolonged. Such is the objective in increasing a systems' flexibility.

3.3 Adding Flexibility in Optimization

The first step in incorporating flexibility in the design of complex engineering system is to determine potential additional (current or future) customer needs and the ensuing missions M_i and functional requirements FR_i . Mission flexibility is then injected into the design process by adding the additional functional requirements to the current functional requirements as given by Eq. 3.2. In the case that the predicted and current functional requirements are supportive and realizable, the resulting system would be able to perform both missions with minimal if any decrement to either. In this degenerate situation the two missions can be collapsed into one.

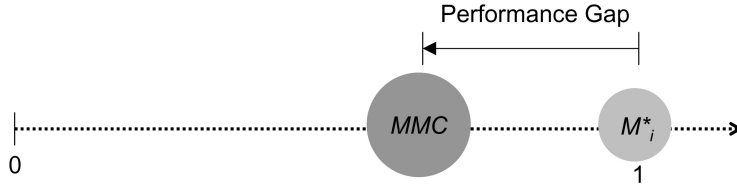


Figure 3-1: The Performance Gap between the MMC and an OPD

3.3.1 The Performance Gap

In the case when the missions have non-supporting Functional Requirements, optimizing the system over the current and predicted FRs would yield an averaging of performance that might preclude the system from performing either mission well enough to yield value, maintain superiority in the case of a weapon system, or retain competitive advantage in the case of a commercial system.

This averaging effect is depicted in Fig. 3-1. A systems' performance of the i th mission is measured by determining the fulfillment of the mission objective function, M_i . As shown in Eq. 3.2, M_i is comprised of the functional requirements FR_i 's needed to perform the i th mission. Accordingly, the performance of the optimized Multi-Mission Capable (MMC) system, along the dimension of any individual mission i , is evaluated by assessing the MMC's fulfillment of the M_i . As shown by [8], the evaluation of OPD_i , M_i^* , represents an upper bound for the i th objective function. Indeed, it stands to reason that a system optimized for one mission objective would perform that objective as well, if not better, than a system optimized for multiple objectives. The performance of the MMC is then normalized by M_i^* , the evaluation of OPD_i in the same objective function. Plotting both the MMC, and i th OPD, on the M_i axis depicts the loss in mission performance suffered by fielding a MMC over an OPD. Truncating the segment of the axes from 0 to the i th objective value attained by the MMC gives Fig. 3-2, and shows the normalized performance gap of the MMC compared to OPD_i

In the same manner, the performance of the MMC is evaluated in the dimensions of each additional mission. The resulting graphs are combined, as shown with three

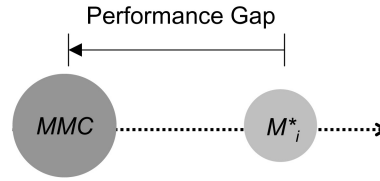


Figure 3-2: Trimmed axes: the Performance Gap between the MMC and an OPD

missions in figure 3-3. This visual depiction is a starting point, or benchmark in our design space. Additionally, it gives a simple way to show performance bias of the MMC toward more important, or more likely, missions.

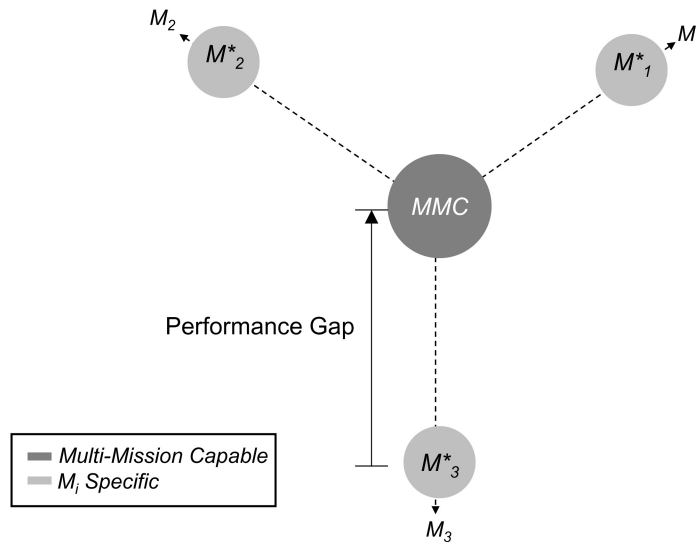


Figure 3-3: The Performance Gap of the MMC compared with each OPD

The center circle represents a Multi-Mission Capable (MMC) system whose objective function includes the functional requirements for each mission. The distance between an OPD and the MMC represents a difference in performance, as captured by the value of the objective function, and is termed the performance gap. The reader is reminded that high-performance is a requirement for these systems, and versatility in mission capability is a value adding feature. To overcome the performance gap, and include flexibility, a platform approach is used.

3.3.2 Platform and Frame Approach

Designing families of products from a common platform has proven to be a valuable option across numerous industries. The commercial benefits of platform design have been widely studied and established from the standpoints of design [11], production [14], inventory [1] and support. In these cases, however, the benefits of introducing a platform are offset by a reduction in performance of the individual platform derivatives [8].

If two systems are dissimilar, or even similar but designed independently, the commonality of the architecture and the summation of common pieces will be small. Systems that are similar, and designed with similarity in mind, can employ a platform and platform derivative approach. We start with the definition of a product platform used by Meyer and Lehnerd (1997):

A product platform is the set of parts, subsystems, interfaces, and manufacturing processes that are shared among a set of products, and allow the development of derivative products with cost and time savings.

To this definition, we amend: A platform designed for flexibility has the potential to satisfy the functional requirements of a set of different missions.

Each mission potential is realized by removing some frame pieces required to perform the initial mission, and adding the appropriate frame pieces to fulfill the new mission. Every platform-based mission-derivative has the option to transition into a different mission-derivative. Having only the option allows each mission-derivative to better perform the single mission by reducing the performance gap of the mission-derivative compared to an optimal point design. The underlying platform is then deemed flexible within the set of missions that it can perform.

Each mission specific system starts from a common platform. Affixed to the platform is a frame that tailors the resulting system to a single mission, or platform derivative. A given mission has hardware and subsystems that are needed for the effective execution of the mission. The functionality enabled by these components may or may not be needed in another mission. To transition the platform to another

mission-derivative, excess capabilities from the starting mission-derivative will be removed. Removing the excess frees resources like power, payload, and real estate for the inclusion of mission-critical components used in the new mission. This exchange, with minimal excess carryover, enables each mission derivative to operate with a minimal performance gap. Having an acceptably small performance gap, while possessing the ability to transition mission specificity defines flexibility.

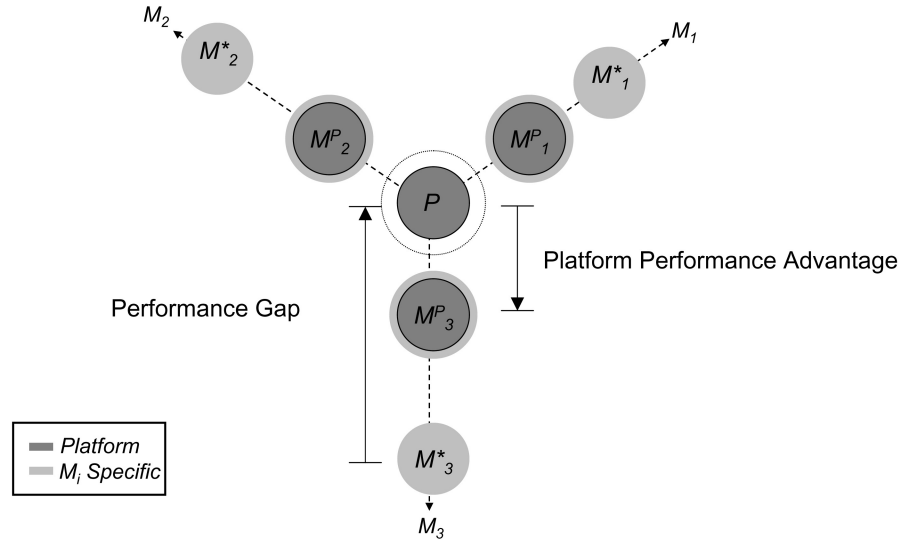


Figure 3-4: The Performance Gap between each OPD and the MMC

3.3.3 Platform-Based Performance Advantage

Requiring flexibility to address multiple missions, this platform and frame approach is shown to decrease the performance gap of each mission derivative over the Multi-Mission Capable (MMC) system, as depicted in figure 3-3. From the reference point of the MMC, shown as the dotted circle around the shaded center platform circle in figure 3-4, the Platform Based Derivatives (PBD) has enabled the depicted Platform Performance Advantage (PPA). Choosing the magnitude of the PPA is a design decision whose controls and consequences will be discussed in the next section.

At this point, we have motivated the need for flexibility and given an overview of how to achieve it. In the following sections, we introduce a concrete optimization framework that enables the inclusion of flexibility in the design of new systems. More-

over, the outlined method quantifies the tradeoffs inherent to flexibility and enables a variety of controls to tune the optimization for the specific application. Finally, the design process for a flexible Unmanned Aerial Vehicle will be presented with the corresponding design results.

3.4 Flexible Systems Optimization Framework

3.4.1 Proposed Framework

The proposed optimization framework starts by individually optimizing each of the considered missions to determine the Optimal Point Designs (OPD). The performance of each of these OPDs is then used as a benchmark to evaluate the performance of the Multi-Mission Capable (MMC) design and Platform Based Derivatives (PBD). The OPD objective value for each mission is an upper bound on the MMC and platform based design that is used to calculate the performance gap.

To generate the platform, a multi-objective optimization problem is solved. The first component of the objective function, *Group Performance* Eq. 3.3, sums the objective value for the considered Platform Based Derivatives, PBD. Each PBD objective value is normalized by their respective OPD objective values. For example, at a given level of platforming, PBD_i might perform the i th mission 70% as well as an OPD. The 30% reduction in performance (of the PBD_i compared to the OPD_i) is the previously discussed performance gap. Considering N missions, the limit on Group Performance will be N .

The normalized performance metric can be used as is, or can be converted into an economic cost in dollars. Associated with each PBD is a cost function (value change of PBD per percent performance change) that captures the value gained for increasing performance of a PBD, or value lost by decreasing the performance. The conversion, defined by the market or customer, gives an economic consequence of the performance gap associated with fielding a system that has less performance than the maximum potential, or OPD.

$$Group\ Performance = \sum_i \frac{Objective_i^{PBD}}{Objective_i^{OPD}} * (\Delta value_i / \Delta performance_i) \quad (3.3)$$

Maximizing the Group Performance objective function would return each of the OPDs. However, prohibitive factors such as the time and monetary costs associated with design, development, installment, training, and support for N OPDs is not a feasible solution in some industries. A platform and frame architecture is introduced to give single systems the capabilities needed to perform one mission, OPD_i , and the option to transition to another mission, OPD_j . The common parts across all OPDs is the platform. Again, this commonality is manifested in system architecture, interfaces, subsystems, parts, etc. As the following sections will show, the extent of the commonality is a design variable that can be tuned for a customer, or market.

The platform is generated by adding a penalty to the Platform Objective function for using different parts in each PBD. A commonality constraint is generated for each element in the design vectors X_i that has the potential to be part of the common platform. The commonality constraints are then dualized and summed into a Commonality Penalty, Eq. 3.4. Dualizing the commonality constraint allows each to be violated, for an associated price. The allocation of that price, relative to the group performance decrement, will ultimately determine which variables the optimizer will include in the platform.

$$Commonality = \sum_i \sum_{j,j \neq i} \sum_k f [X_i(k) - X_j(k)] * G(k) \quad (3.4)$$

To model the problem accurately, $f(k)$ should quantify the cost of using different parts in one or more OPDs. Generating $f(k)$ will be problem specific. If the cost $f(k)$ is assumed linear, $G(k)$ is a regular dual variable. Otherwise, $G(k)$ can be seen as a dual gain. The Platform Objective is then,

$$Platform\ Objective = (Group\ Performance) - (Commonality\ Penalty) \quad (3.5)$$

The first step is to determine $f(K)$, assign a value for each dual variable, and optimize the new platform objective. The dual gain $G(K)$ can be tuned by the designers to emphasize the relative importance and benefit of adding each element to the platform. $G(k)$ will be further discussed in the tuning section. A weighting factor, $\lambda \in [0 : 1]$, is then introduced to trade emphasis between commonality and performance.

$$\text{PlatformObjective} = \lambda (\text{Group Performance}) - (1 - \lambda) (\text{Commonality Penalty}) \quad (3.6)$$

Varying λ during successive optimizations will create a Pareto front of optimal platform derivatives that increase in platform content as λ decreases. We return to figure 3-3 to examine the effects of platforming at the limits. If all the weight is placed on Group Performance, ($\lambda = 1$), the original optimal one-point designs will be returned. In our terminology, each mission derivative will comprised entirely of mission-specific frame, and there is no platform ($\lambda = 0$). Conversely, placing almost all the weight on commonality or platforming (λ approaches 0) will yield the Multi-Mission Capable (MMC) design for each mission specific derivative. In this degenerate case, there is no frame, only platform.

3.4.2 Platform Tuning and Selection

An example of the Platform Objective is presented to introduce numerical conditioning and design parameters that allow the flexible system to be tuned as to reflect the customer's needs. Starting with Group Performance, each objective function in the summation is normalized by the OPD value. This simple numerical conditioning changes the performance loss of each system to a percentage of the OPD value. The vector S_i allows the designer to select the relative importance of the performance for each system. For an equal emphasis on each mission, S_i are simply set to 1.

The Commonality Penalty in this case is captured as a squared difference of potentially common design elements. The value of each dual variable $G(k)$ is a weighting

factor for each element considered in the optimization. For example, choosing a large value of $G(k)$ for the elements that set the fundamental architecture, interfaces, cost drivers, highly integrated systems, etc, will place emphasis on establishing a platform containing these elements. A low value of $G(k)$ corresponds to cheap or easily exchangeable parts that can be tailored to the individual PBD with little penalty during transition. The dual prices are set by the industry, application, and discretion of the designers. As a simple example, each dual variable could quantify the average cost over the i missions of the piece they represent.

$$Objective = \lambda \sum_i \frac{Objective_i}{Objective_i^*} * S_i - (1 - \lambda) \sum_{j,i \neq j} \sum_i \sum_k \left(\frac{X_i(k) - X_j(k)}{\frac{1}{2}(X_i(k) + X_j(k))} \right)^2 * G(k), \quad (3.7)$$

Platforming, and particularly designing a flexible platform, consists of a series of tradeoffs made based on design space exploration and an understanding of the market or customer as a time evolving entity. Beyond tuning for flexibility, there are significant considerations in selecting the optimal platform that are discussed in work of [11] and others. One could start with the construction of Pareto fronts that depict the tradeoffs of Group Performance, Commonality, acquisition cost, value, reliability and additional metrics important to the customer. The idea of trading performance for reduced cost has been extensively demonstrated in the literature; the interested reader is referred to [8] for a thorough discussion of the trade-offs between performance and cost in platform design.

3.4.3 Dual Prices

A brief digression is mentioned with special applicability to Linear Programming optimization formulations. The previously mentioned framework dualizes the platform constraints and assigns a dual gain, $G(k)$, to the violation of each constraint. Reconsider the platform formulation in Eq. 3.3. In the case of an LP formulation, the constraints for generating the MMC would be equality of design elements k . Solving the dual of this problem would yield the marginal costs, $G(k)$ associated

with violating the k th constraint. In this formulation, the $G(k)$ have been determined by the relative change in value per change of performance for each system, $(\Delta value_i / \Delta performance_i)$, as defined by the market or customer. These dual prices can aid designers in selecting which elements should be in the platform.

3.5 Conclusion

An optimization framework was presented herein to design flexible systems and to quantify the trade-offs inherent to adding flexibility. A few options were presented and discussed with respect to formulating the objective function of the optimization. Additional controls were also discussed to help the designer tune the optimization based on the preferences set by the customer.

The next chapter presents a case study that provides a concrete illustration of the proposed design cycle for flexible systems. Moreover, design decisions that are better understood in the context of an example are presented at the end of chapter 4. The case study will entail the design of a mission flexible Unmanned Aerial Vehicle, starting with the customer needs, and resulting in flexible platform based UAVs. In the process, we will quantify the Performance Gap of adding flexibility and show how the proposed platform approach yields a performance advantage for the fielded systems. The design cycle will end with a set of platform based UAV designs.

Chapter 4

Case Study: Unmanned Aerial Vehicles

4.1 Introduction

The case study will start with a description of missions for military rotorcraft UAVs, as well as a driving need for mission flexibility in this area. A brief discussion of the UAV's architecture, and corresponding simulation, will be provided. The task of designing a mission flexible UAV will then be cast into the framework that was previously outlined. The results will show the performance, cost, and time tradeoffs associated with departing from OPDs to field platform based designs with added mission flexibility.

It is worth noting a few facts and assumptions before embarking on the case study. As will be explained in the section on tractability, the chosen UAV allowed for direct measurements, and accurate calculations to establish the merit of the proposed design framework.

Similarly, the helicopter considered has remarkable flexibility owed to the standardized interfaces of most pieces, and structural excess enabled by scaling benefits. Standardization of each interface may increase the cost, and reduce the integration, of full scale systems. However, the only standardization that has value in this framework is in the interfaces of the main design drivers. Such an approach is already in

use in full scale helicopters [6], automobiles, and the Joint Strike Fighter.

The problem is additionally formulated to address the author's perception of the military's needs. The UAV's modeled herein will be optimized to address these needs, and to be flexible to address other needs that might arise in time. While the vehicle of choice is an excellent research testbed, the author is not indicating or implying that it should be considered for military fielding.

4.2 The Missions

The missions will be defined, and described, starting with customer needs and following the progression in Eq. 3.1. The resulting Mission Definitions M_i , and ensuing Functional Requirements FR_i , populate Tab. 4.1. In this table, the FR's are the objectives that drive vehicle design. There are, of course, other requirements that are modeled as constraints in the optimization.

To build the table, a set of customer needs have been identified corresponding to both current and predicted future needs. Presently, the military employs UAVs for short-range missions of loitering, inspection and patrol. Additionally, UAVs are used for long distance reconnaissance where the UAV must be capable of traveling great distances to find and follow the Named Areas of Interest, NAIs.

Fielded UAVs deployed in urban situations currently avoid detection with high altitude, quiet operation and little or no measurable heat signature. However, more sophisticated detection technology on the part of the adversary, or enhanced ambush or bomb detection added to our UAVs could easily drive their mission to the street level. Presently fielded UAVs would be ill suited to this new need. A potential solution under active investigation proposes highly agile fast flying UAV rotorcraft capable of dashing in and out of hot spots more quickly than they can be tracked and disabled. We define this mission as Street Level.

The Loiter mission, on the other hand, optimizes the system configuration for high endurance flight and maximum sensor payload. As a reminder, Table 4.1 has been constructed to reflect the functional requirements of each mission. The FR

Customer Needs	Mission Definition, (M_i)	Functional Requirements ($FR_{i,j}$)
Agile, Aggressive	$M_o \equiv$ Air Show	Angular Rates (+) Acceleration (+)
Loiter, Inspect	$M_1 \equiv$ Loiter	Endurance (+) Sensor Payload (+)
Find/Follow Long Distance NAI's	$M_2 \equiv$ Search and Recon (Confirm/Deny)	Range (+) Time on Target(+)
Street Level	$M_3 \equiv$ Urban Agile	Acceleration (+) Max. Velocity (+)

Table 4.1: Determining functional requirements from customer needs

for Endurance and the FR for Time on Target are both measured as flight time, but written differently to address the corresponding needs of the mission. The + sign following the FR's expresses the desire to maximize the FRs. Mission M_o is a currently existing UAV described in the subsequent section.

4.3 Model and Design Variables

The UAVs designed herein are based on the autonomous helicopter, Figure 4-1, currently used as a research testbed in the Laboratory for Information and Decision Systems at MIT [5]. The MIT helicopter is configured for the mission of aggressive acrobatic maneuvers defined as M_o , with a subsection of its total components designated as design variables X_o .

Seven of the eight design variables shown in Table 4.2 describe rotor geometry, engine parameters, payload and the structure (sub-frame). Combined with the cruise speed, this design vector X_i represents the main drivers that change the mission capabilities of the baseline helicopter M_o to meet the requirements of the other missions M_i . The majority of the other helicopter descriptors not captured in X_i are set to the nominal value of the baseline helicopter to reduce the computational requirements. The remaining set of descriptors, like boom length, change as a function of the X_i . For example, the X_o helicopter employs 680mm main rotor blades with symmetric airfoils. Linearly increasing the length of the rotor blades, and corresponding rotor disk diameter, requires extending the tail rotor rearward by using a longer tail boom.



Figure 4-1: MIT X-Cell 60 Helicopter, X_o

A host of other secondary variables are changed to accommodate variations of the primary design drivers, X_i .

As a mental exercise to see the interplay of the design variables, one can start with the above X-Cell 60 helicopter M_o . The high maneuver margin enables impressive agility. This is obviously a good initial point for the urban helicopter M_3 . Trying to achieve a longer range or flight time, however, would necessitate a plurality of changes to X_i , among which is additional fuel. The increase of fuel weight above baseline would lower the thrust to weight ratio and decrease the maneuverability. Examining the superset of functional requirements for the three missions shows that many are nonsupporting.

4.4 Tractability

The problem formulation for this case study has been posed in a tractable manner. Each of the elements considered in the design vector can be purchased as off-the-shelf parts, or modified from off-the-shelf parts by an expert R/C helicopter pilot in a negligible period of time. This formulation allows exact prices to be associated with each element in the design vector. As the results show, there can be two orders of magnitude of difference in FRs between OPD helicopters. It should be clear that

Category	k	Design Parameter $X_i(k)$	Range
Rotor	1	Main Rotor Radius	$.550m - .950m$
	2	Main Rotor CL_0	$0 - 3^\circ$
Engine	3	9.9cc Nitro	$1.6kW$
	3	15 cc Nitro	$2.2kW$
	3	22.5 cc Gas	$1.6kW$
Payload	4	Payload	$0 - 2.6kg$
	5	Ext. Mounting hard.	$\in (0, 1)$
	6	Av. Mounting Hard.	$\in (0, 1)$
Sub-frame	7	Helicopter Sub-frame	$\in (0, 1)$
Airspeed	8	Cruise Velocity	$0 - 30m/s$

Table 4.2: Design driving variables $X_i(k)$

the wealth of readily available parts allows the X-Cell helicopters to be modified into vastly different flying machines. Additionally, using available parts, and an expert pilot, allows accurate calculations of the associated time to build each helicopter, or transition the mission specificity of a helicopter from one to another. The inherent advantage of this strategy is to decouple calculated results from approximations or guesses. As a final advantage, this formulation allows the resulting helicopters to be tested to establish the accuracy of the modeling.

4.5 UAV Architecture

A flexible architecture has been established to enable a miniature rotorcraft to change from one mission profile to another in a timely and cost effective manner. Each mission derivative helicopter starts from a common platform. A platform is defined as a summation of pieces common to all mission derivatives that has the ability to satisfy the set of requirements for each given mission. Affixed to the platform is a frame that tailors each UAV to a single mission. Having only the ability, and not the physical hardware and software for each mission, allows each helicopter to better perform a singular mission. Should the need arise to change the mission profile, parts of the frame may be added, subtracted, or exchanged. In this sense, the helicopter is deemed flexible within a subset of missions.

A brief description of the UAV architecture will enable the reader to better understand and interpret the results. For a detailed description of the initial helicopter, X_o , the reader is referred to [5]. Conceptually, the UAV is first decomposed into a helicopter and a vibration isolated avionics package.

4.5.1 Helicopter

The helicopters designed herein are based off Miniature Aircraft's X-Cell 60 hobby helicopter. The helicopter has a dry weight of 7 lbs (without engine or main rotor) and is capable of carrying payload close to 13 lbs. The helicopter is inherently quite flexible in configuration. It is predominately constructed with a series of parallel planes separated by stand-offs akin to those used to separate stacked computer boards. Increasing internal space, to house the larger engine for example, is accomplished by increasing the length of the frame stand-offs. Miniature size, and the ensuing scaling benefits, allow the helicopter to have the structural excess to handle a variety of engine powers with minimal performance penalty.

As will be discussed in the section on payload, part of the helicopter structure is not sufficiently strong to satisfy all the considered missions. To meet the strength requirements of some missions, the structure needs re-enforcement. Such re-enforcement is unnecessary, or excess, in other missions. Placing an industry specific gain on this penalty enables the results to be applied to other areas.

4.5.2 Main Rotor

The main rotor disk creates lift, which can be vectored - or tilted - to supply forces and moments on the helicopter. The performance of the the disk is changed by varying the length and camber of the airfoils comprising the disk. Symmetric 680mm airfoils are used in acrobatic flight which often involves inversion. Symmetry of the airfoils enable approximately equal lift to be generated in the positive or negative direction before the blades enter a stall condition. Cambered, 950 mm blades would be employed for heavy lifting.

4.5.3 Engine Options

Three engine options are considered, each using a two-cycle combustion process. The Nitro class of engines are piston driven glow plug configurations that burn a mixture of methanol, nitromethane, and oil. The smaller engine, .6 cubic inches (10 cc), is 21.2 oz (600 g) and outputs 2.2 horsepower. A larger engine bore of .9 cubic inches (15cc) outputs 3 horsepower with a trimmed weight of 19.2 ounces (547 g). These high revving engines, around 15,000 RPM, achieve an incredible power to weight ratio by burning a mixture of fuel and oxidizer. Accordingly, their fuel consumption is quite higher than the third option. A spark ignition engine running a standard two-cycle mixture of gasoline and oil constitutes the third option. With 1.37 cubic inch displacement (22.5cc), the engine generates a maximum of 2.2 horsepower. Weighing in at 56 oz (1.58 kg), it has a significantly lower power to weight ratio than either Nitro option. However, it has a 10% torque advantage over the largest of the Nitro engines. Moreover, the enhanced efficiency enables a four fold increase in flight time over a similarly configured helicopter running a .90 Nitro engine.

4.5.4 Payload

Six of the available 13 lbs of payload are utilized by the avionics box. The remaining available payload, up to about 5.7 lbs (2.6 kg), can be divided between the helicopter and avionics box. The binary design variables $k \in (5, 6)$ in the design vector capture the inclusion of the mounting hardware required to secure the payload. One type of payload mounted to the helicopter is additional fuel tanks. For the avionics box, a plurality of sensors could be added to meet the mission requirements. Mounting sensors requires the addition of the avionics mounting rails, to be affixed to the avionics mounting hard-points. Such avionics options are further discussed in the three tiered architecture section. In missions requiring a high maneuver margin, such as the Street Level mission, the helicopter will not be loaded to the maximum potential gross takeoff weight. Instead, it will be loaded to the optimal gross takeoff weight. As a consequence of additional payload, the substructure for the parallel plates that

house the main rotor shaft and transmit forces and torques from the main rotor to the helicopter need to be enhanced over the baseline configuration. The engineers at X-Cell provided a heuristic to reinforce the substructure for payloads above 10 lbs. This is achieved doubling up the parallel plates, i.e., using two plates on each side instead of one.

4.5.5 Avionics Box: Three tiered Architecture

The avionics box weighs 6.2 lbs and is capable of autonomously guiding the helicopter with acrobatic maneuvers en route. It has a modem down link to allow for ground operators to monitor the status of the UAV, and a miniature video camera that relays the view from the cockpit. The base configuration of the avionics box is constant for each mission and possesses more than adequate capabilities to supply low-level control to the UAV. It may be considered as having excess capabilities for a mission like loitering. However, it is beyond the scope of this work to re-design the avionics box. Instead, an architecture is proposed for the partitioning and update of the avionics box to thwart component obsolescence. The update philosophy is applicable to numerous other electronics systems.

The flexibility of the avionics box is henceforth considered. This thesis proposes a three tiered architecture for said box, and discusses the ramifications of such architecture. It is accepted that rapid advances in technology over the long life cycle of the avionics box will lead to component obsolescence. Interestingly, the time and cost to transition components, as well as the need, naturally establishes two subsections of the avionics suite. The Inner tier on the example vehicle is the TP400 real time operating computer. The TP400 runs legacy code on an operating system that is no longer supported. Upgrading this component would require substantial cost and time. However, the TP400 is more than adequate to control the helicopter, and will not need upgrading under the proposed architecture.

The second tier is the avionics sensors. The sensors have a defined I/O interface, and can therefore be upgraded with relative ease. The inertial navigation system and the Global Positioning System are in an industry of rapid advancement. For

example, the original Ashtech G12 GPS unit was successfully upgraded to a WASS enabled unit from the same manufacturer. This transition allowed the avionics box to increase the fidelity of its absolute position.

The outer tier has a specified power and serial driver interface. In one instance, the outer tier is the fastest laptop computer available with a serial port. It is used to run high-level path planing that requires real-time optimization. Since the outer tier passes way points and maneuver execution commands to the flight computer via a simple, well defined interface, it can be transitioned with little fear, cost, or time. For different missions, the outer tier be can tailored to fit large external sensors, cameras, or other devices that require vibration isolation from the helicopter.

There are four hard mounts on the outside of the avionics box that allow for the mounting of external sensors. A plurality of adapting structures can be attached to these points to create the necessary interface for additional sensors. One example used for a laser range finder is shown in Figure 4-2. In order to maintain effective vibration isolation, the principal inertial axes must align with the principal geometric axes of the avionics box. Provisions have therefore been made to balance out any additional payload.

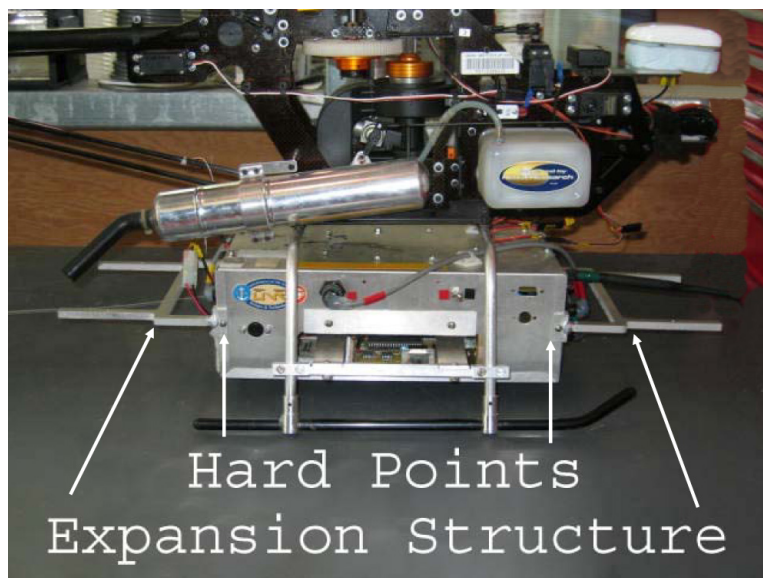


Figure 4-2: Avionics expansion structure mounted to hard points

4.6 Simulation

4.6.1 Model

In order to assess the tradeoffs inherent to optimization, an accurate model must be at the core of the simulation. In this case, the simulation was adapted from the one used to validate the flight control system of M.I.T.'s autonomous helicopter. Keeping the design variables within the applicable range of the model ensures good prediction of the performance characteristics that a realizable UAV would exhibit.

4.6.2 Simulated Test Flight

The simulation begins with a design vector that represents the physical parameters of the helicopter, and the cruise velocity. The secondary design variables, such as the boom length and main rotor RPM, are then calculated as a function of the main design vector X_i . The simulation starts by creating the helicopter described by the input vector. This helicopter is then flown through a prescribes test flight (Figure 4-3), generating the flight data used to assess its performance.

The mission starts with by commanding maximum takeoff. Once the helicopter is airborne, the controller (a finite state machine) switches to way-point navigation mode. It is commanded to the cruise altitude, where it accelerates to the cruising velocity specified in the design vector. Data collected from the simulation is used to assess the performance of each helicopter with respect to the functional requirements for all the considered missions. The output vector contains the payload, flight time, range, maximum forward velocity, and maximal vertical acceleration. This formulation enables direct comparison of each helicopter against the functional requirements for each mission.

To facilitate accurate comparison between the tested helicopters, the simulation optimizes the gross takeoff weight of the helicopter, and measures all of the functional requirements shortly after takeoff. This ensures a conservative bound on the maximum speed and acceleration achievable by the UAV. It us unknown a priori

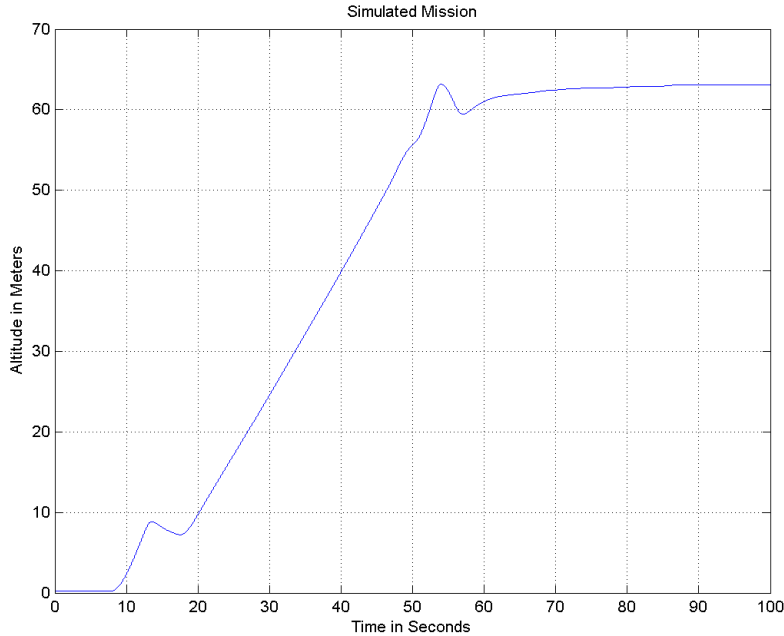


Figure 4-3: Simulated test flight to evaluate Functional Requirements

what portion of the available payload will be devoted to "payload", such as sensors, and what percentage will be fuel. Using the same philosophy of airplane design, the available payload can be traded between fuel and "payload". In this simulation, the payload is assumed to be used entirely as fuel. Thus bounding the range of each vehicle. Such a vehicle can be viewed as a scout with the included small remote camera. If, for example, a mission for firefighters required a 1 kg infrared camera, that would be 1 kg less of fuel, and a resulting decrement in range. In short, the simulation determines the optimal takeoff weight of the vehicle to maximize the functional requirements of a given mission, and satisfy the flight constraints listed below.

4.6.3 Constraints

There are five constraints imposed on the helicopter model (Table 4.3), three of which are the roll, pitch and yaw stability of the helicopter. Another constraint limits the time to rise of the helicopter to less than 40 seconds. The final constraint imposes a limit on deviation from the cruise altitude. Doing so prevents excessive overshoot

and precludes helicopters that exhibit unstable modes, ex phugoid.

Stability	$p \leq 1$ $q \leq 1$ $r \leq 1$
Rise Time	$h(t = 40) \geq h_{cruise}$
Deviation	$(h_{cruise} - \delta) \geq h(t \geq 40) \leq (h_{cruise} + \delta)$

Table 4.3: Constraints Imposed on UAV

4.7 Rigid Design

4.7.1 Initial configurations

The Autonomous Acrobatic helicopter project at M.I.T. started with a X-Cell 60 helicopter powered by a Nitro .90 engine. The vehicle was a good testbed for developing and demonstrating autonomous acrobatic maneuvers. Performance of the initial helicopter is captured in table 4.4. The reader is reminded that the six pound avionics box is not considered available payload. In addition to the avionics box, the initial Nitro .90 helicopter carries .56 L of fuel. The fuel is denoted as payload for constancy with subsequent simulation results.

Design Parameter $X_i(k)$	Value	Functional Requirement	Value
Main Rotor Radius	680mm	Payload	.56 kg
Main Rotor CL_o	0	Flight Time	9.8 min
Engine	Nitro .90	Range	4.3 km
Payload	.56 kg	Max. Velocity	24.5 m/s
Ext. Mounts	0	Max. Vert. Accel	1.46 m/ss
Avionics Mounts	0		
Sub Frame	0		
Cruise Velocity	8 m/s		

Table 4.4: Characteristics for Baseline Nitro .90 UAV

As the research needs of the group changed, a helicopter capable of heavier lifting and longer duration flight was needed. Some of the helicopters were transitioned from Nitro engines to gasoline engines. Performance changes in the helicopter are

noted in Table 4.5. The endurance and maximum velocity characteristics are more conservative on the gas helicopter than the Nitro .90. The performance of the Nitro .90 has been studied under a variety of atmospheric conditions, whereas the gas helicopter has much fewer data points at the current time. As the results will show, however, the conservative estimates did not precluded the gas engine from ending up in two of the three OPDs.

Design Parameter $X_i(k)$	Value	Functional Requirement	Value
Main Rotor Radius	700 mm	Payload	.56 kg
Main Rotor CL_o	0	Flight Time	38.8 min
Engine	Gas	Range	18.1 km
Payload	.56 kg	Max. Velocity	16.89 m/s
Ext. Mounts	0	Max. Vert. Accel	1.38 m/ss
Avionics Mounts	0		
Sub Frame	0		
Cruise Velocity	8 m/s		

Table 4.5: Characteristics for Baseline Gas UAV

4.7.2 Optimal Point Designs

For the Loiter mission, M_1 , the Functional Requirements maximized were endurance and sensor payload. The Optimal Point Design for the Loiter mission is described in Table 4.6. In this mission, both external fuel tanks and avionics mounting hardware will be required; thus both the external payload binary and avionics binary were set to one.

The Loiter mission presented the most interesting results of all the OPDs. As expected, the more efficient gasoline engine was selected, along with cambered main airfoils. However, the optimal length of the main rotor blades was a "short" 680mm. Reviewing the optimization history revealed that larger blades, having a higher aspect ratio and lower operational RPM, did not achieve the longest flight time. Figure 4-4 compares the engine torque of two helicopter whose difference is the main rotor size (with appropriate boom and tail rotors). The 680mm blades enable a lower engine torque in steady level flight, which corresponds to a decrease in fuel consumption,

and increase in flight time.

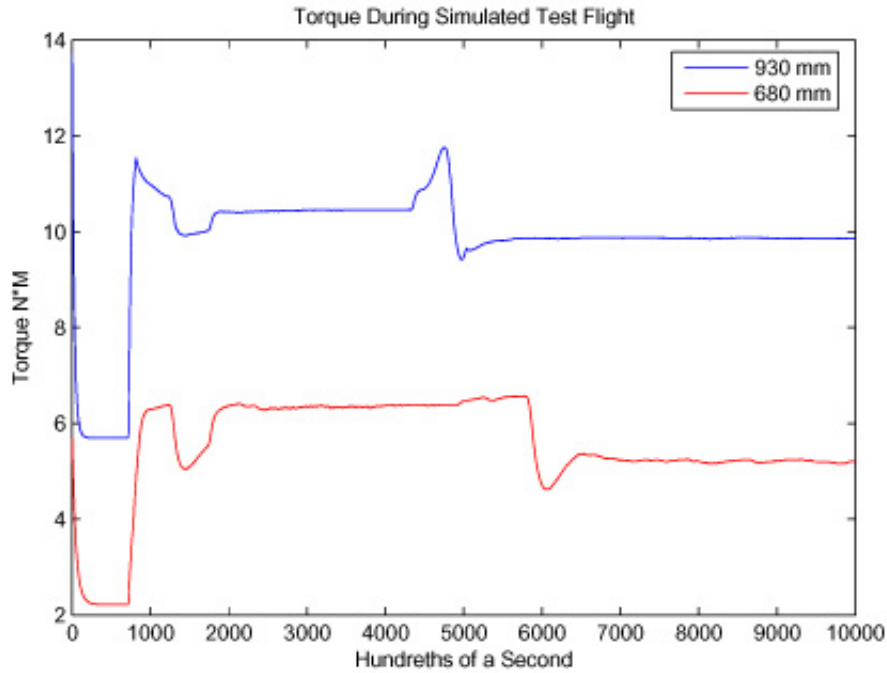


Figure 4-4: Main rotor effect on engine torque during simulated test flight

Design Parameter $X_i(k)$	Value	Functional Requirement	Value
Main Rotor Radius	.680mm	Payload	2.6 kg
Main Rotor CL_o	-2°	Flight Time	162 min
Engine	Gas	Range	51.8 km
Payload	2.6 kg	Max. Velocity	9.28 m/s
Ext. Mounts	1	Max. Vert. Accel	1.48 m/ss
Avionics Mounts	1		
Sub Frame	1		
Cruise Velocity	5.49 m/s		

Table 4.6: Characteristics of Loiter OPD

The search and reconnaissance mission, M_2 , maximized the FRs of range and time on target (measured as endurance). The performance of the search and reconnaissance OPD is listed in table 4.7. As expected, the UAV utilizes the largest main rotor size, and largest fuel capacity. Flying at a faster speed than the OPD loiter helicopter, the search and reconnaissance helicopter covers approximately 1.8 times as much distance as the loiter UAV. However, the search and reconnaissance UAV has only two-thirds

the flight time of the Loiter UAV.

The first and second OPDs differ in main rotor radius, by the inclusion of the avionics mounts in the first OPD, and by the cruising velocity. It will be shown later that the avionics mount has less than 1% effect on the performance of these helicopters. The main rotor, on the otherhand, enables the significant difference in capabilities between these two helicopters. To isolate the effects of the rotor, the cruise velocity of the search and recon mission matched to the cruise velocity of the loiter mission. Lowering the velocity of the search and recon UAV extends the flight time to 131.1 minutes. This is, of course, still only 81 percent of the flight time achieved by OPD_1 . Additionally, the reduced velocity drops the range of OPD_2 to 47.7 percent of the range at the optimal cruise speed.

Design Parameter $X_i(k)$	Value	Functional Requirement	Value
Main Rotor Radius	950mm	Payload	2.6 kg kg
Main Rotor CL_o	-2°	Flight Time	107.3 min
Engine	Gas	Range	92.4 km
Payload	2.6 kg	Max. Velocity	16.7 m/s
Ext. Mounts	1	Max. Vert. Accel	2.55 m/ss
Avionics Mounts	0		
Sub Frame	1		
Cruise Velocity	14.7 m/s		

Table 4.7: Characteristics of Search and Reconnaissance OPD

The final OPD considered was for the street level mission, M_3 . Table 4.8 captures the performance of OPD_3 . Interestingly, this OPD ended up very close to the stock acrobatic helicopter, the X-Cell .90 Nitro. The notable difference is a 30 mm increase in main rotor radius. The stock X-Cell .90 helicopters use symmetric airfoils for the main rotor to enable equal thrust in the inverted direction as is available when flying right side up. Hobby helicopter of this nature are flown in acrobatic competitions with the flight style aptly termed 3D. The testbed helicopter used to develop autonomous acrobatic maneuvers was based off this design.

The simulation predicts that using symmetric airfoils instead of cambered airfoils for the main rotor has the added advantage of lower required torque at the optimal

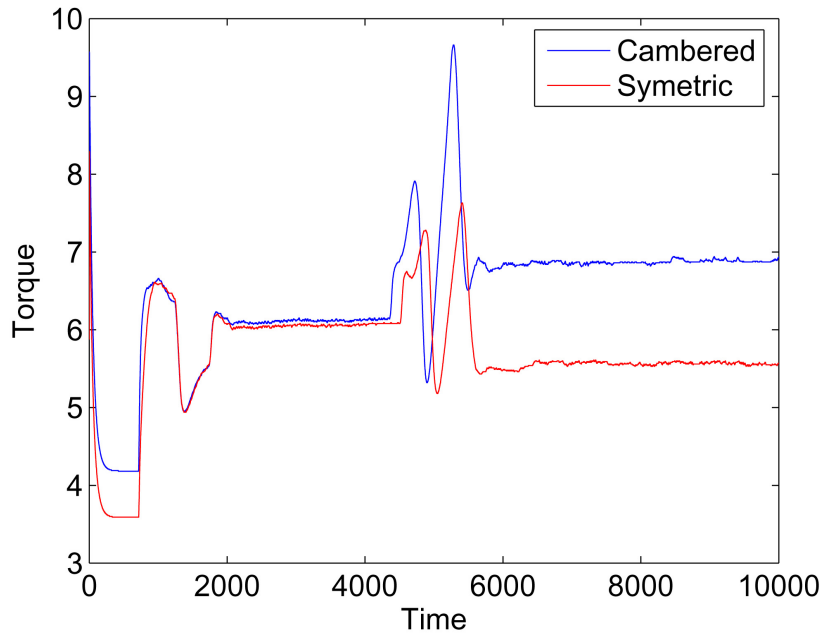


Figure 4-5: Torque during simulated test flight of OPD_3 .

flying speed of 20.3 m/s. Symmetric airfoils enable the helicopter to operate at the optimal speed with 19.2% less torque than cambered airfoils would require. Thus, at the optimal speed, the helicopter with symmetric airfoils has a higher percent of excess engine capabilities for accelerations, termed maneuver margin. Figure 4-5 shows the torque difference of flying the same helicopter with symmetric rotor blades, or cambered rotor blades.

Design Parameter $X_i(k)$	Value	Functional Requirement	Value
Main Rotor Radius	710mm	Payload	.34 kg
Main Rotor CL_o	0	Flight Time	4.4 min
Engine	Nitro 90	Range	4.26 km
Payload	.34 kg	Max. Velocity	46.19 m/s
Ext. Mounts	0	Max. Vert. Accel	2.62 m/ss
Avionics Mounts	0		
Sub Frame	0		
Cruise Velocity	20.3 m/s		

Table 4.8: Characteristics of Street Level OPD

OPD_i is a peak performer at i th mission. As such, it provides the customer with mission superiority as long he or she seeks to engage in the i th mission. However, the

passing of time may bring forth a change in the customers' needs to the j th mission. If the performance of OPD_i in the j th mission is sufficiently low, such that the customer needs to replace it, system has slipped into mission obsolescence. Resulting from the point optimization process (discussed in chapter 2), OPD's are often inflexible to significant change in mission focus.

4.7.3 Optimal Point Designs: Addressing New Missions

We assess now, the performance of each OPD with respect to the mission it was intended to fill, and when used to fulfill the other missions considered in this case study. The mission effectiveness of the j th OPD, evaluated against M_i , is compared in matrix 4.1. The matrix captures OPD_j as the row, and the i th mission objective function M_i as the columns. The elements in each column are normalized by the performance of the i th OPD. Thus, $P_{OPD}(i, j) = M_i(OPD_j)/M_i(OPD_i)$. Accordingly, the diagonal entries are equal to unity.

$$P_{OPD} = \begin{bmatrix} 1.0000 & 0.6216 & 0.5360 \\ 0.7106 & 1.0000 & 0.6692 \\ 0.0976 & 0.0479 & 1.0000 \end{bmatrix} \quad (4.1)$$

It is clear that fielding the i th OPD gives the customer superiority in the i th mission. The question of mission flexibility asks how each OPD would fare if the mission needs change over time. The off-diagonal terms for a row depict the performance of the OPD if used to fulfill the needs of a mission other than what it was designed for. Selecting the second row, OPD_2 designed for the Loiter mission, shows that this UAV would perform the street level mission with two thirds (66.9%) the effectiveness of OPD_3 . This is likely not a viable option for a customer that needs mission superiority.

Should the customers' needs change during the designed service lifetime of OPD_2 , the customer faces a dilemma. In that case where OPD_2 is minimally flexible, corresponding to many highly integrated point designs, the system would have little ability to refocus its capabilities from M_2 to M_3 . Hence it would be considered ob-

solely. OPD_2 can be retired in favor of fielding OPD_3 , or it can be used in a highly suboptimal way, a way which was neglected in its initial design.

4.7.4 Multi-Mission Capable System

The key then, is to predict other needs, or missions, the customer might face during the entire design lifetime of the system. The resulting Multi-Mission Capable system is shown in Table 4.9, and as the fourth row in 4.2. For M_2 and M_3 , the MMC exhibits increased performance over any off diagonal UAV. In fact, the MMC is only bested by OPD_2 used to address M_1 , entry $P(2, 1)$. The abilities of the MMC to fulfill each mission can be depicted visually in fig. 4-6. For this MMC design, the Performance Gap is greatest in M_1 , and least in M_2 . The relative weights of the missions can be changed in the formulation of the optimization objective function to generate a Pareto Front of Performance Gaps based on mission weightings for the MMC. One would likely employ this approach if fielding an MMC was the ultimate goal.

While the MMC is better, in an average sense, than most off-point usage of the OPD's, it is, at best, only 86 percent as effective as an OPD used in the mission it was designed for. Reducing this difference, or performance gap, is motivation for flexible design and the focus of the ensuing platform approach.

$$P_{OPD} = \begin{bmatrix} 1.0000 & 0.6216 & 0.5360 \\ 0.7106 & 1.0000 & 0.6692 \\ 0.0976 & 0.0479 & 1.0000 \\ 0.5374 & 0.8660 & 0.7167 \end{bmatrix} \quad (4.2)$$

4.8 Flexible Designs

Flexibility is achieved when a fielded system can refocus its capabilities to address needs (missions) that arise during the service lifetime of the system. The measure of flexibility is a three fold combination of performance, cost, and time. The first assessment is the performance of the system at the currently needed mission. The fielded

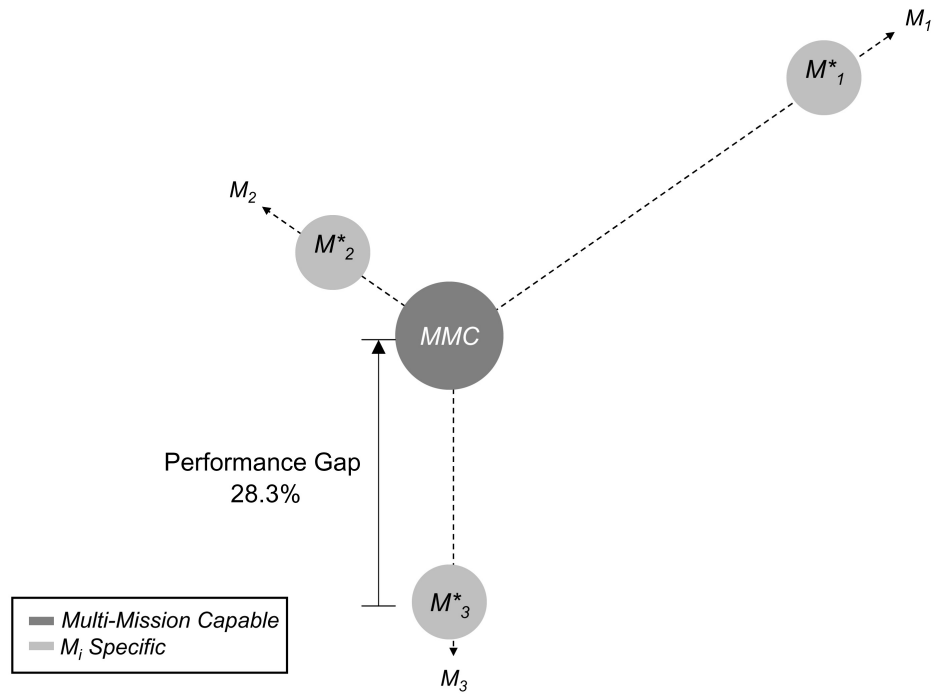


Figure 4-6: Performance Gap of MMC compared to OPD_i

Design Parameter $X_i(k)$	Value	Functional Requirement	Value
Main Rotor Radius	940mm	Payload	1.97 kg
Main Rotor CL_o	-2°	Flight Time	76.8 min
Engine	Gas	Range	80.98km
Payload	1.97 kg	Max. Velocity	19.93 m/s
Ext. Mounts	1	Max. Vert. Accel	2.39 m/ss
Avionics Mounts	1		
Sub Frame	1		
Cruise Velocity	18.2 m/s		

Table 4.9: Multi-Mission Capable UAV

system's competitive edge dulls as the mission requirements change with time, and as the component base of the fielded system ages. At each time of this measurement, we normalize the fielded system's performance by a potential OPD designed at for that mission, at that time (with the appropriate design lead time). In hyper-competitive markets, the pertinent measure is the performance of what you are fielding compared to what you (or the competition) could be fielding. Normalizing at each time step by the OPD for a given mission shows the performance gap of the fielded system compared to the best possible system to address that mission- a technologically current, Optimal Point Designed system- a new OPD.

Resharpener of the fielded systems' competitive edge is achieved through the refocusing of capabilities. In the context of this work, refocusing occurs by exchanging components (frames) of the fielded system. The cost of the exchange, as well as the down-time of the system during the exchange, are the final two measures of flexibility.

As obsolescence sets in, the customer will look at the option of upgrading the current system, as compared to purchasing a new one. The essential equation weighs the performance of transitioning the fielded system (compared to current OPD) against the cost and time required to make the transition. If this measure of flexibility is favorable, the option is exercised. Making the option worthwhile is object of this work, and the platform approach.

The ensuing sections will discuss how the measures of flexibility - Performance, Cost, Time (PCT)- change with the degree of platforming. The reader is reminded that zero platforming corresponds to OPDs, and the upper bound of platforming is the MMC.

At each level of platforming, the PCT matricides will show the flexibility of the Platform Based Designs (PBD). For example, during a systems' fielded lifetime, it may be forced to address a mission other than the one it was originally designed for. The inherent performance of the fielded system at the new mission is a baseline of performance. The flexibility of the system is the ratio of performance enhancement (output) to the cost and time required to realize such an enhancement (inputs), Eq. 4.3.

$$Flexibility = \frac{\Delta Performance}{Required Cost and Time} \quad (4.3)$$

As mentioned, the designed UAVs are based off an inherently flexible model helicopter. The manifestation of such is the ability to transition each helicopter to another with a cost and time bounded by the procurement price and build time of an OPD helicopter for the new mission. While other applications may have unbounded cost and time to transition, there is no loss of generality assuming that one would not wish to exceed the bound. Indeed, one would not want to pay more to transition an old system to meet a new mission than the procurement price of an OPD for the new mission.

4.8.1 Platform Based Designs

The platform is defined as the summation of parts common to each mission specific Platform Based Design (PBD). It can also be thought of as the portion of the system that remains constant through all transformations of mission specificity. A baseline level of platforming is established as all the elements not captured in the primary or secondary design variables. These variables have a lesser impact on mission performance, and are hence set to the nominal value of the baseline helicopters. They are necessarily part of the platform, as is the avionics box (without the optional mounts).

P^α (Name if applicable)	Platform Elements	Frame Elements
$P^o = MMC$	MT+S, Engine, MR	<i>null</i>
P^1	MT+S, Engine	MR
P^2	MT+S	Engine, MR
$P^3 \approx OPDs$	<i>null</i>	MT+S, Engine, MR
MT+S = Payload Mounts and structure	Engine = Engine	MR = Main rotor

Table 4.10: Platforming Levels Considered

Six of the design drivers listed in Table 4.2 are partitioned into three groups. The inclusion or exclusion of each group in the platform establishes the level of platform-

ing, P^α . The first group, MT + S, corresponds to the payload mounting hardware and the structural reinforcement. Including this group in the platform would mean that each UAV would be built to the highest mission load requirements, and have both payload mounting options. Adding the second group, the engine, to the platform, makes it a constant through each transformation. The final group entails the camber and radius of the main rotor, aptly abbreviated as MR. The four level of platforming, P^α , are detailed in Table 4.10.

The MMC, P^o , should be thought of as the case where all Platform Based Designs (PBD) are composed of only platform. There is no addition or subtraction of frame pieces to tailor the UAV to the differing missions. We increase the flexibility of the system by removing the main rotor from the platform and allowing it to be tailored for each individual mission. Corresponding to P^1 , the main rotor has become a frame piece.

4.8.2 Platforming Level P^1

The largest driver governing the performance of a UAV is the main rotor. Taking the main rotor out of the platform, thus giving each UAV the degree of freedom to optimize the rotor for the specific mission, significantly reduces the performance gap of PBD_i as compared to OPD_i . Taken from the reference of the MMC, the each PBD_i has a Platform Performance Advantage (PPA). Figure 4-7 shows the PPA for PBD_3 . There performance increase is clearly substantial. In fact, the PPA for missions one and two place the PBD's so close to the OPDs that they were left out of the figure for clarity. Allowing the main rotor to be optimized for the individual mission yields a strong performance advantage.

The following Performance matrix ($P_{transition}^1$), 4.12, is read similarly to P_{OPD} . The P_{OPD} matrix, however, measured a fielded OPD's inherent performance at each mission. This is a limit case of the $P_{transition}^\alpha$ matrix wherein there are no pieces changed, requiring no cost or time to transition. The same is true of the MMC. The $P_{transition}$ matrix is equivalent to P_{OPD} in the case of the MMC. Since there is no frame, and hence not transition of pieces, P_t measures the MMC's inherent ability to

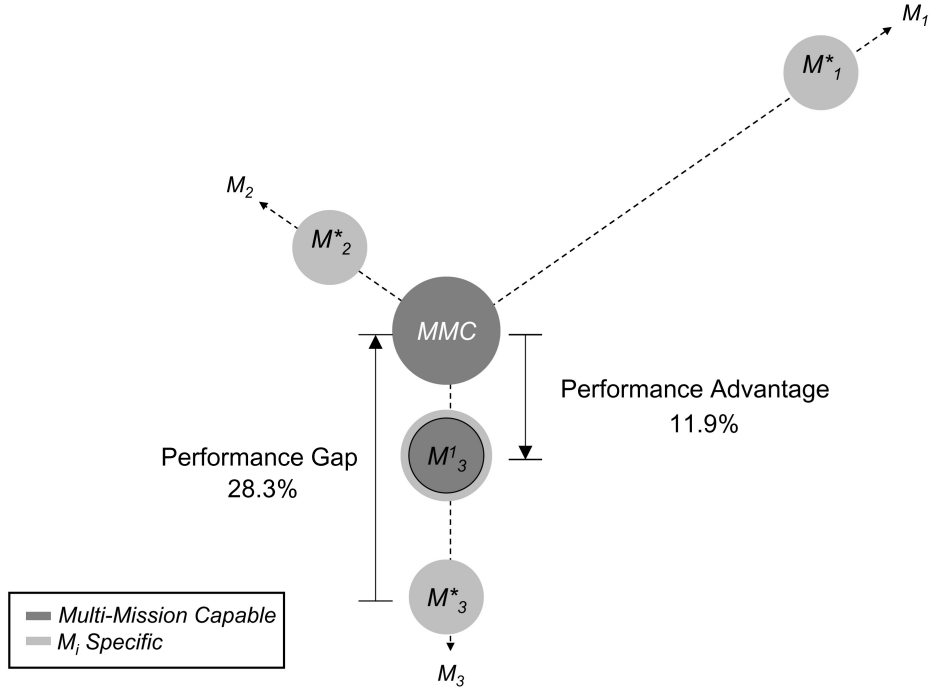


Figure 4-7: Performance Gap and Platform Advantage

satisfy each M_i (which is how P_{OPD} was defined). Additionally, there is no cost nor time required to transition the MMC.

These transition matrices capture the starting system, PBD_j^α , as the j th row. Transition turns PBD_j^α into PBD_i^α , the i th column is the matrix. Visually, PBD_j^α enters the matrix through the j th row, and exits as a PBD_i^α from the i th column. Element $P^\alpha(j, i)$ shows the performance of the transitioned system measured by M_i , and normalized by OPD_i . Essentially, the P matrix gives the performance gap of the transitioned PBD_i^α compared to the OPD_i .

At P^1 level of platforming, and ensuing excess, the performance of PBD_i^1 is independent of the starting configuration PBD_j^1 , or any PBD_j^1 the fielded system had been over its lifetime. By allowing only the main rotor to vary between PBDs, the maximum and minimum performance that PBD_j^1 can achieve are one and the same. Reducing the number of elements that comprise the platform will invoke a dependence on all past configurations of the fielded system.

$$P_{transition}^1 = \begin{bmatrix} 1 & .9937 & 0.8357 \\ 1 & .9937 & 0.8357 \\ 1 & .9937 & 0.8357 \end{bmatrix} \quad (4.4)$$

Associated with the performance of transitioning a system $P_{Transition}$, there is a Cost and Time to achieve the transition. These are recorded in the respective $C_{Transition}$ (4.5) and $T_{Transition}$ (4.6) matrices. Both are read in the same manner at the P matrix. Transitioning from PBD_j to PBD_i has a $P(j, i)$ performance gap, requires $C(j, i)$ cost fraction of a new OPD_i , and takes $T(j, i)$ percent of the time to build a new OPD_i .

The reader is reminded that at the P^1 level of platforming, each transition requires only switching the main rotor (and tail boom). The costs in $C_{Transition}$ 4.5 differ due to the differing costs of the frame pieces (Main Rotors) that enable the transition, and the differing procurement costs of the OPD for each mission. If the frame pieces and OPDs had the same cost, the transition costs would be identically the same for this level of platforming.

$$C_{Transition} = \begin{bmatrix} 0 & 0.1060 & 0.0842 \\ 0.0794 & 0 & 0.0842 \\ 0.0794 & 0.1060 & 0 \end{bmatrix} \quad (4.5)$$

The time to transition each helicopter is the same at this level of platforming. Notice that the loiter UAV requires the added substructure, and both payload mounting options. The Street level mission does not, however. In this case, both OPD UAVs have the same build time, as installing the extra components during the initial assembly requires negligible additional time. However, as will be seen shortly, there is a significant time penalty to retroactively install the payload mounting hardware, or the substructure, after the UAV is build and fielded (assembled and flight tested). Ergo, one aspect of flexibility relates the performance decrement of fielding options unneeded by the current mission, to the cost and time savings if mission transition is desired.

$$T_{Transition} = \begin{bmatrix} 0 & 0.1136 & 0.1136 \\ 0.1136 & 0 & 0.1136 \\ 0.1136 & 0.1136 & 0 \end{bmatrix} \quad (4.6)$$

4.8.3 Platforming Level P^2

We further decrease the level of platforming by removing the engine from the platform. At this level, P^2 , only the mounting hardware and substructure re-enforcement are included in the platform. The performance gap for this level of platforming, captured in 4.15, is arguably negligible for the considered systems. Notice the cost and time transition matrices in comparison to the next reduction in platforming, P^3 .

$$P_{Transition} = \begin{bmatrix} 1 & .9937 & .9978 \\ 1 & .9937 & .9978 \\ 1 & .9937 & .9978 \end{bmatrix} \quad (4.7)$$

$$C_{Transition} = \begin{bmatrix} 0 & 0.1060 & 0.2327 \\ 0.0794 & 0 & 0.2327 \\ 0.2196 & 0.2442 & 0 \end{bmatrix} \quad (4.8)$$

$$T_{Transition} = \begin{bmatrix} 0 & 0.1136 & 0.4318 \\ 0.1136 & 0 & 0.4318 \\ 0.4318 & 0.4318 & 0 \end{bmatrix} \quad (4.9)$$

4.8.4 Platforming Level P^3

At the lowest level of platforming, P^3 , each UAV is entirely composed of frame pieces. However, transitioning from OPD_j to PBD_i^3 does not yield OPD_i in all cases. The rule for transition is that all necessary additions are made, but any excess from is carried from one OPD to another. One can consider the modifications irreversible, or requiring significantly more cost and time to reverse than is worthwhile (as in this case). Such an assumption may be partially true (economically or feasibly partially

reversible) in other fields, and is left to the discretion of the designer.

Under this transition policy, and P^3 level of platforming, the performance of the transitioned system is a function of each system it has been in the past. Consider each mission as a state in a Markov chain. Each time the system transitions states, it acquires all necessary mounting hardware. Accordingly, this can increase the excess carried over to each mission.

$$P_{Transition}^3 = \begin{bmatrix} 1 & 0.9937 & .9978 \\ 1 & 1 & .9979 \\ 1 & 1 & 1 \end{bmatrix} \quad (4.10)$$

$$C_{Transition}^3 = \begin{bmatrix} 0 & 0.1060 & 0.2327 \\ 0.0935 & 0 & 0.2327 \\ 0.2757 & 0.2857 & 0 \end{bmatrix} \quad (4.11)$$

$$T_{Transition}^3 = \begin{bmatrix} 0 & 0.1136 & 0.4318 \\ 0.2045 & 0 & 0.4318 \\ 0.6364 & 0.5455 & 0 \end{bmatrix} \quad (4.12)$$

4.8.5 Accrued Excess and Scaling Considerations

For example, start out with an OPD_2 . It can transition to PBD_2^3 with a given performance penalty of .0021%. However, if OPD_2 is first transitioned to PBD_1^3 , then to PBD_3^3 , it will acquire additional excess. The result is a further reduction (.45%) of the .0021. Due to the afore mentioned scaling benefits of the considered system, the loss is not bad. The reader is reminded, however, that a gain should be applied to this loss based on the system considered. In other areas, this performance loss through accrued excess can be quite significant. In the case of rocket design, the payload mass fraction of the launch weight is sufficiently small that such excess may not be worthwhile.

4.8.6 Differing Platforms

Finally, we examine change in PCT for different levels of platforming. As the example, we will consider the differences (Δ 's) between P^2 (PCT^2) and P^3 (PCT^3). This comparison boils down to the including or exclusion of the mounting hardware and sub-structure reinforcement. First, we note that the increase (Δ) in acquisition cost for including MT + S in the platform (P^2) is zero for M_1 , 1.38% for M_2 , and 5.94% for M_3 .

As the PCT matrices show, there is a small (relative to this example) change in the performance and cost of the transitioned PBDs through based on the level of platforming. The time to transition, however, is significantly different. The time required to add the mounting hardware and or structural reinforcement during the build process is negligible. However, having add any of these components after the system is fielded, requires significant disassembly and reassembly time. Moreover, there is an added flight readiness testing time when required after a significant disassembly. As one might expect, including the potential forward compatibility has a performance penalty, and transition cost and time savings. The relative weights of the loss and gain, taking into account the probability of transitioning, enables a designer to decide which level of forward compatibility is desired.

$$P_{\delta_{2,3}} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & .0063 & .0001 \\ 0 & .0063 & .0022 \end{bmatrix} \quad (4.13)$$

$$C_{\delta_{2,3}} = \begin{bmatrix} 0 & 0 & 0 \\ 0.0140 & 0 & 0 \\ 0.0561 & 0.0415 & 0 \end{bmatrix} \quad (4.14)$$

$$T_{\delta_{2,3}} = \begin{bmatrix} 0 & 0 & 0 \\ 0.0909 & 0 & 0 \\ 0.2045 & 0.1136 & 0 \end{bmatrix} \quad (4.15)$$

4.9 Conclusion

In this chapter, we have applied the ideas and methodologies presented in this thesis to the design of mission-flexible Unmanned Aerial Vehicles. It was shown that Optimal Point Designs (OPD) provided the highest performance of any considered system with respect to the mission they were designed to fulfill. Akin to OPDs in general, it was also shown that the OPD UAVs were ill suited to meet missions that were significantly different than the one they were originally designed to meet. Indeed, the Loiter mission, and Search and Reconnaissance mission, have arguably similar objective functions. Therefore, using one to fulfill the needs of the other does not necessarily drive the system to obsolescence. However, using either to fulfill the Street Level mission (with the ensuing performance gap in excess of 90%) would not be a viable option.

Next, we examined the possibility of building a Multi-Mission Capable system. As explained in chapter 2, we discovered that designing a system to excel at the functional requirements for all missions resulted in an averaging effect that precluded the MMC from yielding high performance in any mission.

A platform and frame approach was implemented to create Platform Based Designs (PBD) that could be transitioned from one mission focus to another with an acceptable cost and time to transition. Four levels of platforming were considered. Assessing the Performance, Cost, and Time to transition (PCT) matrices for the PBD's, within the context of Eq. 4.3, enabled us to quantify the differences in flexibility of each level of platforming. Moreover, the benefits and detriments of adding elements to the platform were found by examining the difference in PCT matrices between different levels of platforming.

In the case of the UAV, allowing individual optimization of the main rotor for each specific mission (P^1) yielded significant performance benefits over the MMC (P^0). Reducing the level of platforming to P^2 brought each PBD within 1% of the OPD values. Infact, the scaling benefits of the UAV allowed the inclusion of mounting hardware and structural re-enforcement (P^2) with marginal performance

penalty. Further decreasing the platforming to P^3 yielded a negligible performance increase, but mandated a significant increase in time to transition from mission 3 to either of the other two missions. This result illustrates that adding a potential for forward compatibility, that would otherwise require significant time (complexity) to include after the system has been fielded, can significantly increase the flexibility of a fielded system.

Chapter 5

Conclusion and Future Work

This thesis has presented a methodology which which to design flexible systems. Tools to asses the relative merits of increasing the flexibility of a system were provided in the form of performance cost and time to transition matrices. Applying the framework to the design of an miniature unmanned helicopter evoked discussion of some intricacies surrounding the art.

The first part of this work motivated the need for flexibility in hyper-competitive systems with long fielded lifetime. Flexibility has been described as the ability of a system to maintain the competitive advantage despite environmental change. A rigid system, on the other hand, is unable to adapt to changing mission requirements.

Chapter 2 explained the competing forces at play pushing system to be more rigid, or more flexible. Optimizing designs for point performance was shown to create top-notch systems (OPDs) that were, however, rigid in their mission focus. Next, we explained how obsolescence- the driver behind the pursuit of flexibility- sets in as systems age. The exposed rigidity of Optimal Point Designs (OPD) motivated the addition of flexibility through the inclusion of capabilities in excess of the original mission needs.

Chapter 3 presented a systems-level approach for embedding flexibility in the design of a new engineering system, along with the potential performance penalties, and a mitigation strategy adapted from platform design. The methods were presented in a general framework as to aid in portability to other areas. A strategy to increase

flexibility was adapted from the art of platforming. A flexible platform, from the viewpoint of flexibility, would enable the customer to exchange only the obsolete components (frame), for sufficiently low cost, and sufficiently short downtime. In the transition, only the obsolete components are upgraded. That which is not upgraded, and remains constant through all transitions of mission focus, is termed the platform.

Chapter 4 presented the core of this work. The case study entailed the design of a mission flexible Unmanned Aerial Vehicle, starting with the customer needs, and resulting in flexible platform based UAVs. More than containing an example of UAV design, it illustrated how the advantages and costs of flexibility could be quantified. Different levels of platforming were contrasted by examining the performance enhancement gained through transition of mission focus (from PBD_i to PBD_j), and the associated cost and time to complete the transition. Examining the PCT matrices for the PBDs compared to the PCTs of the MMC (in the context of the flexibility equation, 4.3) revealed that platform based designs indeed yielded a Platform Performance Advantage (PPA) over the Multi-Mission Capable system. The extent of the PPA is then a design decision that is tuned to meet the customer, or market, needs.

Flexibility, at this time, has been limited to prediction and potentials. We will now give a window into how potentials may enable flexible systems to adapt better (to unpredicted missions) than rigid systems.

5.1 Future Work

This work hopes to have scratched the surface of flexible design. The author suggests that a continuation of this work would examine some of the following issues.

5.1.1 Potentials For Excess: A Basis to Address New Missions

In the context of this work, we have addressed predicted flexibility. The flexibility of a system was quantified in with respect to a currently contracted mission, and

predicted future missions. Indeed, mission requirements changing beyond what has been *predicted* may expose rigidity in the design of these systems. This is not to say, however, that these systems can only address the *predicted* missions. Throughout the work, we have defined transition as the exchange of frame pieces, not a frame.

Focusing mission potential on the three considered missions of the case study required a full frame. However, focusing the mission potential of the platform for an unpredicted mission may employ frame elements from multiple different platforms. The ability to perform each functional requirement, or summation in the case of missions, should be viewed as a basis of performance.

Unfortunately, the performance basis is not orthogonal, as the frame pieces compete for resources. Correspondingly, the actual feasible design space for an unpredicted helicopter will be a subsection of the presented mission basis.

The author suggests finding a change of basis to map the potentials for excess to a orthogonal coordinate system.

5.1.2 Scalability

The author will try to include some insights to aid in the mapping of these results to the design of other systems. The large market for model helicopters that comprises the UAV has made it possible to purchase what would otherwise be one-off designs for a commodity price. This is outside the feasible space of many full-scale cutting-edge systems. Accordingly, it should only be considered possible to achieve this purchase price if procuring a fleet of any given type of UAVs.

As was discussed in the payload section of chapter 4, there is a small performance penalty due to structural excess. Placing an industry specific gain on this penalty enables the results to be applied to other areas. In a crude sense, the gain should be inversely proportional to the Factor Of Safety used in the industry, which can be thought of as an ability to tolerate excess. For example, an engineer is building ladders with a Factor Of Safety (FOS) of $ord(I) = 1$. Not much gain is needed. Conversely, a rocket scientist with FOS of 1.25 might use a gain of $ord(I) = 1000$ to find the appropriate penalty for excess in said industry.

The author suggest looking into scaling rules that would allow the tradeoffs of performance, cost, and time to be decoupled from specific industries.

5.1.3 Dynamic Force Reallocation

Engaging one's enemy is a dynamic process whose requirements change as a function of both time and adversary. It is therefore important for tools of engagement to be as remoldable as the pursuit itself.

Flexible systems, designed with the outlined platform and frame partitions, can be quickly and cost effectively transitioned from one mission focus to another. In the case of the considered UAVs, a procured fleet could be tailored to combat a specific enemy, or fulfill a needed mission, at each deployment. Thus, the focus of the force can be dynamically reallocated to face different adversaries. The author suggest investigating the merits of such a deployment strategy.

In the course of any work, traveling down one path reveals many interesting side paths. The author has pointed out a few, in the hopes that some may find interest in continuing this work.

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