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Addressing Cost Growth in Spacecraft Acquisition Programs: A Prescriptive Approach

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Cost growth, defined as the act of exceeding a previously allocated budget, is undesirable, but historically rooted trend in spacecraft acquisition programs. In response to this trend, there have been numerous methodologies developed with the objective of reducing the occurrence and magnitude of cost growth in spacecraft acquisition programs. Subsequently, these methodologies have converged upon a similar philosophy in addressing cost growth, which relies on making the assumption that the cost growth experienced in historical spacecraft programs can appropriately predict the expected cost growth in future spacecraft programs; hence cost growth is estimated by analogy. In contrast, this research demonstrates a fundamentally different philosophy regarding cost growth through the provision of a methodology for avoiding and mitigating cost growth not relying on analogies to historical spacecraft programs. As such, this research both complements and expands upon previous methodologies and emphasizes active prevention and correction for avoiding cost growth in spacecraft acquisition programs. Subsequently, this research methodology supplies a means for quantitatively addressing cost growth in programs seeking to acquire spacecraft that are highly innovative (*e.g.,* fractionated spacecraft) and thus cannot be compared to historical spacecraft. The results of this research demonstrate that the methodology is a successful tool for avoiding and, at the very least, mitigating cost growth throughout the respective lifecycle of a given spacecraft acquisition program.

I. Introduction

Historically, the cost of spacecraft has evolved appreciably over their respective programs. Consequently, this evolution rarely leads to spacecraft becoming less expensive relative to their estimated cost during the early stages of their respective program (*e.g.,* NASA Phase A). Most notably, in surveying forty NASA space and science mission programs launched before 2007, these forty spacecraft mission (acquisition) programs saw, on average, a cost growth (increase) *beyond* programmatic reserves, from NASA Phase A/B estimates to cost at launch, of 26.9% (Emmons, Bitten, & Freaner, 2006). Additional studies have found that, for certain NASA space and science mission programs, this cost growth has been, again *beyond* programmatic reserves, as much as 175% or 320 FY2008$M (Freaner, Bitten, Bearden, & Emmons, 2008). The clear concern for future space missions is thus the consistent and appreciable underestimation of spacecraft program costs made during the early stages of a given program; a trend that is, unfortunately, historically rooted in many NASA missions having occurred during the past four decades, and a trend that continues today with some of NASA's most prominent missions (Holtz-Eakin, 2004).

Given the historical prevalence of cost growth in major spacecraft acquisition programs, there have been notable research efforts resulting in the suggestion of approaches for addressing, and thereby avoiding cost growth in a given acquisition program; these methods include The Aerospace Corporation's FRISK methodology and Tecolote's ACE methodology (Tecolote Research Inc., 2009a; Young, 1992). These research efforts have independently sought to discover the specific sources of cost growth in a given program and thereby stem the adverse effects of these sources, namely an increase in cost. Subsequently, these research efforts have collectively identified that there are factors both *internal* and *external* to a spacecraft acquisition program that lead to cost growth (Perry & Bruno, 2008). The internal factors include elements of an acquisition program such as new technology, mass budgets, project management, mission assurance, and systems engineering. And the external factors include elements such as launch vehicle procurement, pre-flight launch vehicle operations, and schedule slips.

While previous research efforts quantitatively addressing cost growth have contributed numerous unique methods for avoiding cost growth in spacecraft acquisition programs, most of these methods share a common reliance on analogy to historical spacecraft programs for estimating cost growth. As such, these research methodologies are inappropriate for addressing, and thereby avoiding and mitigating cost growth in programs seeking to acquire highly innovative spacecraft (*e.g.,* spacecraft interferometers, fractionated spacecraft) due to their

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creation of a new spacecraft acquisition program paradigm having limited, or no historical basis (Lawson, Lay, Johnston, & Beichman, 2007; M. Gregory O'Neill & Weigel, 2009; Michael Gregory O'Neill, 2009; Richards, Szajnfarber, M. Gregory O'Neill, & Weigel, 2009). Subsequently, this research seeks to develop a methodology for avoiding and mitigating cost growth in acquisition programs for highly innovative (and even unprecedented) spacecraft architectures, although, the methodology is broadly applicable to any spacecraft acquisition program. The methodology developed through this research and described hereafter enumerates the manifestation of cost growth in a given spacecraft program through the internal factors of programmatic efficiency and mass budgets. As such, the methodology provides continuous guidance for avoiding and mitigating cost overruns throughout the lifecycle of a given spacecraft acquisition program. In addition, the methodology is purposefully prescriptive thereby differentiating itself from all other cost growth methodologies that opt to use single-point percentages or "lump sums", rather than prescriptive guidance, to avoid cost growth in spacecraft acquisition programs.

II. Motivation

The suppliant question is thus, why do spacecraft cost estimates made during the early (conceptual) design stages of an acquisition program have such a poor correlation with their respective costs after program completion, even when including programmatic cost reserves in the program? The most appropriate, albeit conceptual answer to this question is that spacecraft designs *evolve* over the course of a program lifecycle; this is to be expected given the natural increase in a spacecraft design's technical maturity as it transitions from a paper concept to an flight-ready system. Subsequently, this growth of technical maturity follows a path throughout a program that cannot be known with complete certainty, which gives rise for the need to include programmatic reserves when estimating the cost of a given spacecraft acquisition program. However, based on past NASA mission programs, it is evident that these programmatic reserves still cannot fully combat the appreciable cost growth in spacecraft over their respective acquisition programs. Specific reasons for cost growth - beyond programmatic reserves - have been cited by others and include an improper scope (*i.e.,* lack of technical definition) of the project/system during the early stages of design; need to undercut the cost budget to keep the program "realistic" and competitive in the current government and aerospace acquisition paradigm; and unforeseen technical complexity and thus research and development effort required (Bearden, Freaner, Bitten, Emmons, & Coonce, 2008; Emmons et al., 2006; Perry & Bruno, 2008).

Addressing the issue of a spacecraft's cost growth over its respective program lifecycle is a notable challenge, given the inherent tradeoff between (1) the elements of a spacecraft acquisition program to be analyzed and subsequently used to develop a methodology for addressing cost growth; (2) the resources required to develop the methodology; and (3) the capability of the methodology in avoiding cost growth in future spacecraft acquisition programs. Nevertheless, avoiding and, at the very least, mitigating the cost growth experienced in a spacecraft acquisition program is of keen interest to program managers and stakeholders given the obvious benefits of avoiding cost overruns. This, coupled with the historical underestimation of spacecraft acquisition program costs, provides the fundamental source of motivation for the methodology developed through this research effort.

III. Literature Review

The literature review provides a brief overview of industry-standard cost models and their lack of quantitatively accounting for cost growth in spacecraft programs. Following this discussion, several prominent methodologies specifically developed to address cost growth in spacecraft acquisition programs are discussed.

A. Industry-Standard Cost Models

In the context of a program lifecycle, spacecraft cost estimates made during the early stages of a program often heavily, if not exclusively, rely on industry-standard cost models, which employ parametric-based cost estimating relationships (CERs) (NASA, 2008). However, CERs, and hence these industry-standard cost models, make a critical assumption that a given spacecraft design will not change over the course of its respective program, which precludes CERs from accounting for cost growth in the spacecraft cost estimates they help to quantify. This conclusion is directly evident in surveying many prominent, industry-standard spacecraft cost models such as the Small Satellite Cost Model (SSCM) and the Unmanned Space Vehicle Cost Model (USCM), which derive their respective CERs through regression analyses on *existing* spacecraft, thereby not accounting for the inherent evolution of these spacecraft over their respective programs (Mahr & Richardson, 2002; Tecolote Research Inc., 2009b). Evidently, industry-standard spacecraft cost models share a common neglect in accounting for the cost growth in spacecraft acquisition programs.

B. Cost Growth Methodologies

In recent years, there have been several methodologies developed that to specifically address a given spacecraft's potential cost growth over its respective program, which may complement the cost estimation of that spacecraft using a parametric-based cost model. Note that these methodologies differ from the industry-standard spacecraft cost models in their specific objective of quantitatively and/or qualitatively addressing cost growth in spacecraft acquisition programs. In particular, there are three prominent methodologies that are representative of three of the four most commonly employed paradigms for estimating spacecraft cost growth; they are **(1)** Formal Risk Assessment (FRISK), developed by The Aerospace Corporation (Emmons & Bitten, 2009; Mahr & Richardson, 2002; NASA, 2008; Young, 1992); **(2)** Automated Cost Estimator (ACE) (NASA, 2008; Tecolote Research Inc., 2009a); and **(3)** general programmatic cost reserve (Emmons et al., 2006)[1].

As stated previously, there are four cost-growth estimation paradigms; these are (1) *a priori* probabilistic, (2) *a posteriori* probabilistic, (3) end-cost analogy, and (4) detailed bottom-up. (1) The *a priori* probabilistic paradigm includes cost growth methodologies that quantitatively address cost growth in a given spacecraft acquisition program using probabilistic distributions of an *assumed* form; the FRISK methodology belongs to this paradigm. (2) The *a posteriori* probabilistic paradigm includes cost growth methodologies that quantitatively address cost growth in a given spacecraft acquisition program using probabilistic distributions that *do not have an assumed form*; the ACE methodology belongs to this paradigm. (3) The end-cost analogy paradigm includes cost growth methodologies that quantitatively address cost growth in a given spacecraft acquisition program via a single multiplicative factor; the general programmatic reserve methodology belongs to this paradigm. (4) Lastly, the detailed bottom-up paradigm includes cost growth methodologies that stochastically address cost growth in a given spacecraft acquisition program via the use of scenario-based Monte Carlo Analyses or Markov Processes; these scenarios can be based on any constituents of a program. A succinct overview of these four paradigms is implicitly detailed in the *2008 NASA Cost Estimating Handbook*; this book also provides a good starting point for understanding the cost growth methodologies that fit within these four paradigms as well as their respective inputs, outputs, advantages, and disadvantages (NASA, 2008).

Notably, all four of these cost growth estimation paradigms and the respective methodologies belonging to each provided limited, if any, prescriptive information for avoiding or mitigating cost growth continuously over the lifecycle of a program. Rather, most of these methodologies focus on assigning probabilities of completion at cost, or "lump sum" increases to an estimated spacecraft program cost to "account" for cost growth. In addition, the first three cost estimation paradigms (*i.e., a priori* probabilistic, *a posteriori* probabilistic, and end-cost analogy) contain cost growth estimation methodologies that all share a common philosophy that leads to a reliance on quantifying the cost growth of spacecraft acquisition programs via analogies with historical spacecraft - a subtle, but ever so critical assumption. Consequently, this critical assumption narrows the scope of spacecraft acquisition programs that can be appropriately treated by these methodologies.

IV. Research Methodology

A. Cost Growth Time Interval

An oft-neglected aspect of literature describing the development and application of research having the objective of addressing spacecraft cost growth is the time interval over which cost growth is quantified. The quantification of cost growth within a given spacecraft acquisition program requires both a basis (start) cost and an end (final) cost, the difference and ratio of the latter and former yielding the absolute and percentage cost growth in the spacecraft program respectively. For example, in adopting NASA's program lifecycle framework, cost growth could be quantified from a programs estimated cost at Pre-Phase A (conceptual studies) to the programs cost at the end of Phase D (launch). Regardless of the two "time-points" within a program used to quantify and thus address cost growth, they need to be explicitly elicited rather than leaving the reader to speculate as to the bounds used for cost growth. In the case of this research and subsequent methodology, cost growth is defined and therefore addressed for the time interval between the conceptual spacecraft development stage (NASA Pre-Phase A) and system closeout (NASA Phase F). Thus, the cost growth considered herein encapsulates the evolution of a spacecraft acquisition program and its respective cost from concept development, through launch and mission operations, until system de-orbit and shutdown at end-of-life (EoL). Subsequently, the methodology developed and demonstrated through this research can be continually applied to track, avoid, and mitigate cost growth at any point during a spacecraft acquisition program falling between the two extremes of this time interval.

[1] Please refer to the *2008 NASA Cost Estimating Handbook* for further examples of cost-growth methodologies; note that these methodologies will fall into one of four cost-growth estimation paradigms mentioned hereafter (NASA, 2008).

B. Methodology Overview

This research effort is motivated, just as other cost growth methodologies have been, through the response to the fundamental question, what is the purpose of addressing a spacecraft's respective cost growth? A succinct answer to this question is that addressing spacecraft cost growth is purported to improve the correlation between a program's estimated and actual cost budget. Subsequently, this research effort has lead to the development of a methodology that hopes to confirm this response by focusing on the programmatic efficiency and mass budget elements of a given spacecraft program, which may manifest themselves as cost growth. Specifically, this methodology, as shown in Figure 1, is prescriptive in that, for a given program budget, cost growth in a spacecraft can be actively avoided and mitigated through a formal understanding of how cost growth is continually manifested in the program. In this sense, employing this research methodology provides a means for guiding the cost of a spacecraft acquisition program at a level of technical design via programmatic efficiency and mass budgets such that the *evolution* of the spacecraft design over its respective program does not lead to a cost overrun. Therefore, this methodology implicitly accounts for, and addresses the cost growth of a given spacecraft over its respective program lifecycle in an entirely prescriptive manner, thereby not making any strategy for avoiding or mitigating cost growth dependent on historical spacecraft acquisition programs (*i.e.,* analogies).

$$Time_{Cost\ Growth} \equiv \lfloor T_i, T_f \rfloor \in \lfloor BoL, EoL \rfloor$$

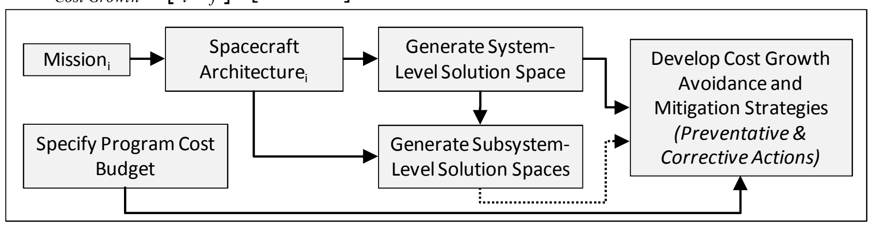

Figure 1. Research Methodology Overview.

The research methodology begins through a specification of the time interval over which cost growth is considered and thus avoided or mitigated. Since this methodology can be recursively applied as a program evolves over time, any cost growth avoidance or mitigation strategies developed by applying the methodology are relevant only at the beginning of the presently defined time interval. The beginning and end of the time interval is denoted by T_i *and* T_f, or the lower *and* upper bound of the time interval, respectively. Therefore, specification of the time bounds for the cost growth is a necessary first step of the methodology. Following this, the spacecraft mission and architecture need to be defined, for example, a remote sensing mission being performed by a monolithic spacecraft. The next crucial element of the methodology is defining the program cost budget at time T_i; this can be specified by a program manager or some other aggregation of the program's respective stakeholders.

With these four elements of the methodology specified, the next step is to generate a solution space at the system-level (*i.e.,* the level at which metrics characterizing a spacecraft encompass the entire spacecraft and its respective program). The system-level solution space(s) can then be refined down to a subsystem-level, if desired. The solution space is used to understand how cost growth is manifested through elements of a given spacecraft acquisition program from T_i forward, and it contains all potential solutions (*i.e.,* candidate spacecraft architectures) that will achieve the previously defined mission objectives. Thus, since every candidate spacecraft architecture in the solution space has an *identical* performance, they are all equivalent in terms of utility - but not cost - provided to the mission stakeholders. Specifically, this research enumerates the solution space, and hence potential for cost growth, through the programmatic efficiency and mass budget aspects of a spacecraft acquisition program.

For a given spacecraft program budget, spacecraft architecture, and mission, these solution spaces can be used to provide a prescriptive means for avoiding or mitigating cost growth in a spacecraft acquisition program on the basis of the dimensions (characterizations) a spacecraft program enumerated in the solution space. Since the program budget will uniquely specify a cost that cannot be exceeded, all the solutions within the solution space will provide the context for how that program budget can be adhered to and, if in the case of a predicted cost overrun, how the spacecraft design or program needs to change to stay within its respective budget. Prescriptions derived from a given solution space therefore lead to the creation of cost growth avoidance and/or mitigation (reduction) strategies, which can be interpreted as preventative and/or corrective actions (to be taken) in a program at time T_i[2].

While the description of this research methodology hereafter provides one instantiation of the specific constituents of the research methodology shown in Figure 1, these are only suggestion and, as such, Figure 1 is purposefully abstract. This abstract depiction of the methodology is intended to enforce the notion that the one should populate each constituent of the methodology with tools/approaches, from generating solution spaces to defining a spacecraft architecture, that best suit the needs of the spacecraft acquisition program at hand.

[2] Given that the research methodology enables the effective management of a given spacecraft acquisition program's cost, it may be particularly valuable to organizations attempting to minimize (or avoid) cost overruns across a portfolio of programs.

V. Case Study

A case study is employed to demonstrate the applicability of, and foster confidence in, the methodology developed through this research effort, which has the objective of providing a prescriptive means for avoiding or, at the very least, mitigating cost growth in spacecraft acquisition programs. Specifically, the case study considers a monolithic spacecraft performing a remote sensing mission. Fortunately, a high-fidelity spacecraft evaluation tool, called the Spacecraft Evaluation Tool (SET), was available to define and generate the constituents of the research methodology described previously. The SET was developed by the author specifically for the purpose of designing and assessing monolithic and fractionated spacecraft, and it was found to be readily extensible to this research methodology (O'Neill 2009; O'Neill & Weigel, 2009). While the SET, and therefore case study could have trivially considered a fractionated spacecraft as the system of interest, a monolithic spacecraft was selected to avoid inadvertently focusing on interesting insights about fractionated spacecraft, which would have ultimately detracted from demonstrating the intrinsic benefits provided by the research methodology.

A. Time Interval

In the case study the time interval, over which cost growth is addressed, is from the spacecraft acquisition program conception and initial concept studies (NASA Pre-phase A) to EoL (NASA Phase F). Therefore, T_i and T_f are the time at program concept studies and closeout respectively (see Figure 2). Any time interval for the case study would have been suitable as it would have readily demonstrated the applicability of the research methodology to any time-period within a given spacecraft program. And keep in mind that this methodology can be recursively applied to any time interval within a given spacecraft acquisition program lifecycle. Subsequently, any cost growth avoidance and mitigation strategies developed are applicable only at time T_i in the time interval because as soon as the program matures, these strategies will necessarily change on the basis of new information and accrued costs.

NASA Program Lifecycle

T_i → **Pre-Phase A:** Concept Studies
→ **Phase A:** Concept & Technology Development
→ **Phase B:** Preliminary Design & Technology Completion
→ **Phase C:** Final Design and Fabrication
→ **Phase D:** System Assembly, Integration & Test, and Launch
→ **Phase E:** Operations & Sustainment
T_f → **Phase F:** Closeout

Figure 2. Time Interval Representation.

B. Mission

The mission considered in the case study is a 7-year, Earth-based, remote sensing mission (RSM). Spacecraft performing such missions make observations of the Earth over a specific range or ranges of the electromagnetic spectrum; often the range(s) is(are) in the visible, infrared, and near-infrared portions of the electromagnetic spectrum. The RSM observations reflect the particular Earth coverage statistics required by the mission at hand and may include observing all/part of Earth's surface, oceans, atmosphere, magnetosphere, weather, resources, health of crops, and/or pollution. The case study considered herein entails a spacecraft performing a RSM with the objective of capturing visible wavelength images of the Earth's surface. The spacecraft therefore has an optical mirror system (*i.e.,* telescope) as its payload instrument that has a 1-meter ground resolution (payload performance). And, for the purposes of this case study, the spacecraft has an orbit altitude and inclination of 700 km and 98° respectively; a common altitude and inclination for Earth-based, RSMs (consider GeoEye-1, Landsat-7, and EOS Aqua).

C. Spacecraft Architecture

The spacecraft architecture considered in this case study (*i.e.,* the system of interest) is a monolithic spacecraft that has the following subsystems: tracking, telemetry, and control; attitude control; guidance control; propulsion; thermal control; structures and wiring; a RSM optical mirror payload (telescope); communications; computer and command & data handling; attitude determination; guidance navigation; and electrical power generation and storage. The collective functionality of these subsystems enables the monolithic spacecraft to achieve the focal mission objective, namely, capturing and transmitting 1-meter resolution, visible-wavelength images of the Earth's surface.

D. Specify Program Cost Budget

The spacecraft program cost budget also needs to be specified at time T_i in the program and must quantify the allowable cost of the program for the specified time interval (*i.e.,* from T_i and T_f). This budget can be determined by a program manager or any aggregation of program stakeholders. Given that this case study is hypothetical, at time equal T_i, the program budget, from T_i and T_f, is assumed to be specified by the program manager and equal to 700 (FY2008$M). Note, as the research methodology is recursively applied over the course of a given program lifecycle, the budget value can be revised based on new information, funding allocations, and accrued costs.

E. Generate System-Level Solution Space

The solution space for the monolithic spacecraft and mission considered in this case study was generated using the Spacecraft Evaluation Tool (SET). The system-level solution space characterizes the aggregation of all spacecraft program constituents, rather than individual subsystems. The solution space contains candidate monolithic spacecraft architectures and specifically characterizes them relative to their respective lifecycle cost, mass, and programmatic efficiency; each of these metrics will be described in turn. For this case study, the solution space provides, at time T_i in the program, estimates of spacecraft cost at time T_f, relative to the estimated final mass of the spacecraft and assumed programmatic efficiency throughout the program lifecycle.

1. System Static Lifecycle Cost

The system static lifecycle cost quantifies the total cost of a given monolithic spacecraft from T_i and T_f, that is, the time interval considered. The lifecycle cost constituents, the sum of which yield the lifecycle cost, include both nonrecurring (NRE) and recurring (RE, aka T1) costs for the spacecraft. Depending on the time interval, the NRE costs may include the cost of researching, designing, developing, manufacturing, integrating, testing, assembling, and launching the spacecraft. And depending on the time interval, the RE costs may include the cost of researching, designing, developing, manufacturing, integrating, testing, assembling, operations support, human labor, and ground station facilities. The totality of these NRE and RE costs is the lifecycle cost of a given monolithic spacecraft over the respective mission lifecycle between the bounds of the specified time interval. The system *static* lifecycle cost is a special form of system lifecycle cost and it quantifies the lifecycle cost of a spacecraft given an ideal lifecycle, that is, there are no launch vehicle or spacecraft on-orbit failures during the lifecycle; hence the system static lifecycle cost is the lower bound cost for a given spacecraft program.

2. System Mass

The system mass is the total mass of the spacecraft, meaning the summation of the mass for all respective hardware constituents present in the spacecraft. The system mass is one of the dimensions along which spacecraft cost growth can occur, since a spacecraft's mass and cost have a strong, positive correlation. In generating the solution space, mass is one of the two independent variables used to explore the manifestations of cost growth in a spacecraft. Therefore, if the expected mass of a spacecraft decreases or increases, the expected spacecraft cost and hence cost growth relative to the program budget, will decrease and increase respectively.

3. Programmatic Efficiency

The programmatic efficiency is defined as the hours expected, to the hours actually required, for completing a given task within a program. The tasks span all elements of a program including activities related to researching, designing, developing, manufacturing, integrating, testing, assembling, operations support, and human labor. In quantifying the programmatic efficiency, these tasks are not separated but rather aggregated due to the fidelity of the cost model in the SET. Given that the SET is conceptual spacecraft modeling tool, the datum for the hours expected, and hence datum programmatic efficiency, is determined from the *2008 NASA Cost Estimating Handbook* and *NASA Cost Estimating Website* (NASA, 2008, 2009). Using these sources, a NASA-standard Beta distribution of costs is employed to establish the cumulative expenditure of costs during a spacecraft's development and, additionally, establish an expected programmatic efficiency for the particular mission and spacecraft considered in this case study. Changes in programmatic efficiency manifest themselves in the form of cost growth and reduction (see Figure 3). If the efficiency of a given program is lower than the datum, thereby implying that the labor force is taking longer than expected to complete the program's respective tasks, then the cost per-unit-time, and hence potential for cost growth increases. Conversely, if the efficiency of a given program is higher than the datum, thereby implying that the labor force is taking less time than expected to complete the program's respective tasks, then the cost

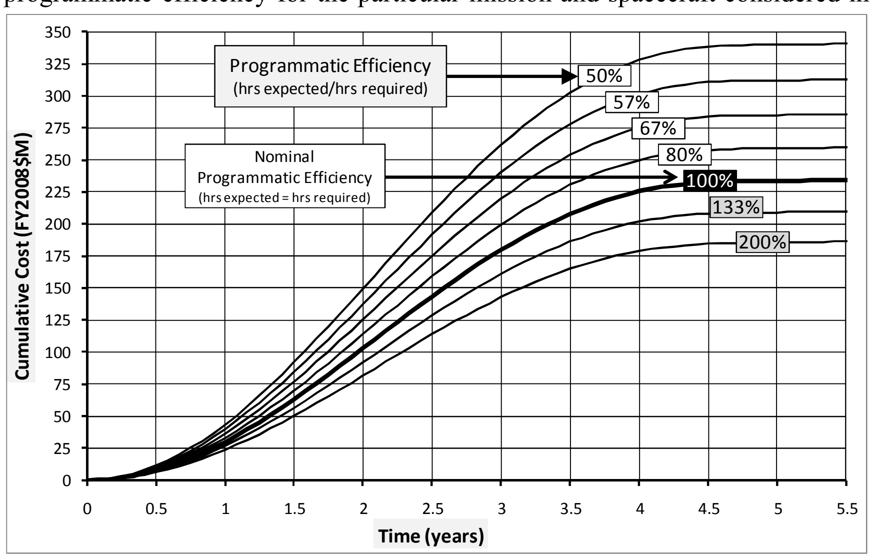

Figure 3. Programmatic Efficiency and Cumulative Cost.

per-unit-time, and hence potential for cost growth decreases. Figure 3 depicts the relationship between cost growth and programmatic efficiency over a notional 5-year development cycle for a monolithic spacecraft as a function of the cumulative cost distribution for that spacecraft. For this case study, the programmatic efficiency was varied between 50% (1 hr expected/2 hrs required) to 200% (1 hr expected/0.5 hrs required).

4. Manifestation of Cost Growth

As mentioned previously, this research methodology seeks to explore and thus prescribe preventative and correction strategies (actions) for avoiding and mitigating cost growth in spacecraft acquisition programs. These strategies are thus developed and executed along the two independent variables of system mass and programmatic efficiency, which characterize a given spacecraft (program) and subsequently may manifest themselves as cost growth in that program (see Figure 4). Before proceeding, it is worth mentioning that there are plenty of other manifestations of cost growth in a spacecraft program that were mentioned earlier, which could have been used to generate the solution space. However, system mass and programmatic efficiency were selected on the basis of their encompassing nature of a spacecraft design and program, and hence cost during the early (conceptual) stages of a program. This is not to say that these two metrics provide a holistic representation cost growth sources, but the manifestation of cost growth through system mass and programmatic efficiency is realistic to many spacecraft acquisition programs, as these two characteristics of a spacecraft (program) inevitably encapsulate numerous other, more subtle, manifestations of cost growth. In the case of mass and programmatic efficiency, sources of cost growth encapsulated by these two metrics include technical immaturity (uncertainty) in a design, requirements creep, and unforeseen programmatic delays. Hence, the use of mass and programmatic efficiency as surrogates for a multitude of cost growth sources is reasonable given the time interval considered in this case study. Subsequently, the solution space uses system mass and programmatic efficiency to enumerate candidate spacecraft architectures. Recall, however, that the research methodology does not prescribe the manner in which the solution space is created; hence, one can use any manifestation of cost growth in a spacecraft acquisition program they would like and still attain the intrinsic value of this research methodology.

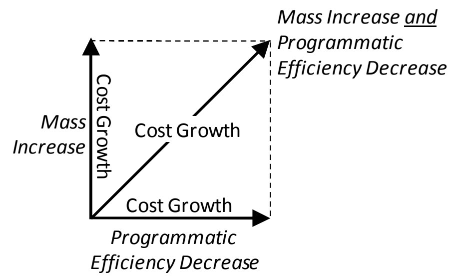

Figure 4. Manifestation of Cost Growth.

5. Case Study Solution Space

As discussed previously, the solution space for this case study consists of candidate monolithic spacecraft architectures relative to their respective system mass, system static lifecycle cost, and programmatic efficiency. All of these architectures provide the same utility to the spacecraft program/mission stakeholders, given that they have *identical* performance characteristics and mission lifetimes. The solution space for the monolithic spacecraft performing the remote sensing mission in this case study is shown in Figure 5. Given the nature in which the SET in evaluates spacecraft architectures, the solution space was developed discretely by iteratively employing the SET to model a monolithic spacecraft relative to different (potential) mass budget allocations and programmatic efficiency values. In addition, and as is shown in Figure 5, for a given spacecraft in the solution space, the mass and lifecycle uncertainty are represented by the error bars around each point. These mass and lifecycle cost uncertainties specifically arise from the parametric nature of the cost model in the SET; note that SET physics-based model, and hence mass, is quantified in an entirely non-parametric nature and therefore the mass uncertainty is deduced from the respective cost uncertainty.

Given the mission and monolithic spacecraft architecture considered in this case study, the SET generated

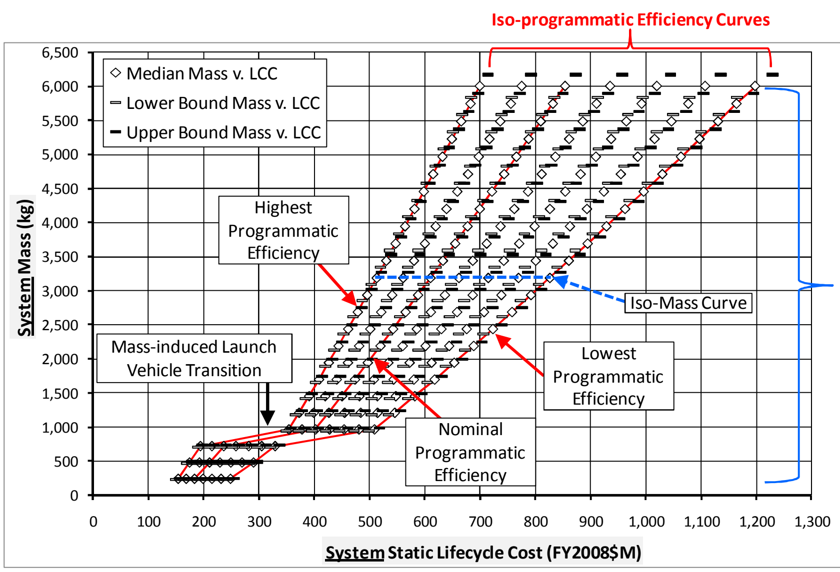

Figure 5. Monolithic Spacecraft Solution Space.

the 168 spacecraft designs shown in the solution space in Figure 5 over the course of 4 days on the basis of varying the efficiency of the spacecraft program and the allowable mass budget. Things worth noting in Figure 5 are the isometric(iso)-programmatic efficiency and iso-mass curves. Intuitively, as the programmatic efficiency and spacecraft mass increase, the expected lifecycle cost of the spacecraft program increases. The other notable observation of the data presented in Figure 5 is that for a given programmatic efficiency, there is a discontinuity in transitioning from spacecraft mass budgets of 750 kg to 1000 kg. This discontinuity specifically arises because the increase in spacecraft mass from 750 kg to 1000 kg (and hence size) necessitates a change of launch vehicles. As such, the launch vehicle used by the monolithic spacecraft, when the spacecraft mass is less than or equal to 750 kg, is less expensive than the launch vehicle used when the spacecraft mass is greater than or equal to 1000 kg.

Before moving to the next stage of the research methodology, it is important to recall the time constant associated with the data presented in Figure 5. The time interval considered in this case study is from program conception (NASA Pre-phase A) to EoL (NASA Phase F), hence the EoL projected spacecraft mass and lifecycle cost in Figure 5 is an estimate made relative to time T_i, or program conception. Therefore, any preventative or corrective actions made on the basis of this information are applicable at time T_i *only* because as soon as time T_i passes, the data set in Figure 5 will need to be updated to account for program costs accrued since T_i.

F. Develop Cost Growth Avoidance and Mitigation Strategies (Preventative & Corrective Actions)

The solution space characterizing the system mass and lifecycle cost, for a given programmatic efficiency, of the monolithic spacecraft performing the mission considered in this case study can be used to develop cost growth avoidance and mitigation strategies. These strategies will guide the evolving design of the spacecraft from T_i and T_f, based on current estimates of the spacecraft lifecycle cost and mass, the allocated cost budget for the program, and the programmatic efficiency, as are depicted in the solution space. The specific cost-growth avoidance and mitigation strategies may include preventative and corrective actions, which increase the probability that the program will come in under, or on budget. The preventative actions specifically prescribe mass and programmatic efficiency *margins* for the current design at T_i that will enable the spacecraft to evolve over the program and remain under budget. Analogously, corrective actions prescribe mass *reductions* or programmatic efficiency *increases* to prevent a currently expected cost overrun at T_i, hence providing a specific set of actions (goals) for which the lifecycle cost of the program can be reduced.

The synergy of the solution space generated in the previous step of the methodology and the introduction of a budget is a prescriptive framework for avoiding and mitigating cost growth. Subsequently, this synergy can be represented in numerous forms, each of which lends itself to the development of particular cost growth avoidance and mitigation strategies. Three such representations are provided in Figure 6, 7, and 8; Figure 6 depicts a two-dimensional solution space and Figures 7 and 8 are an interpretation of Figure 6, which depict lifecycle cost contour curves and cost disparities, for a given programmatic efficiency and system mass, respectively[3].

Figure 6 shows a notional spacecraft evolution path through the solution space at time T_i; this is shown by the solid black line. One can envision that this line shows the evolving nature of the spacecraft (program) mass, lifecycle cost, and programmatic efficiency during the conceptual design stage. The motivation for showing a sample solution path through the solution space is that, in relation to the allowable budget (for this case study the budget is 700 FY2008$M), the solution space can be divided into under budget and cost overrun regions. Subsequently,

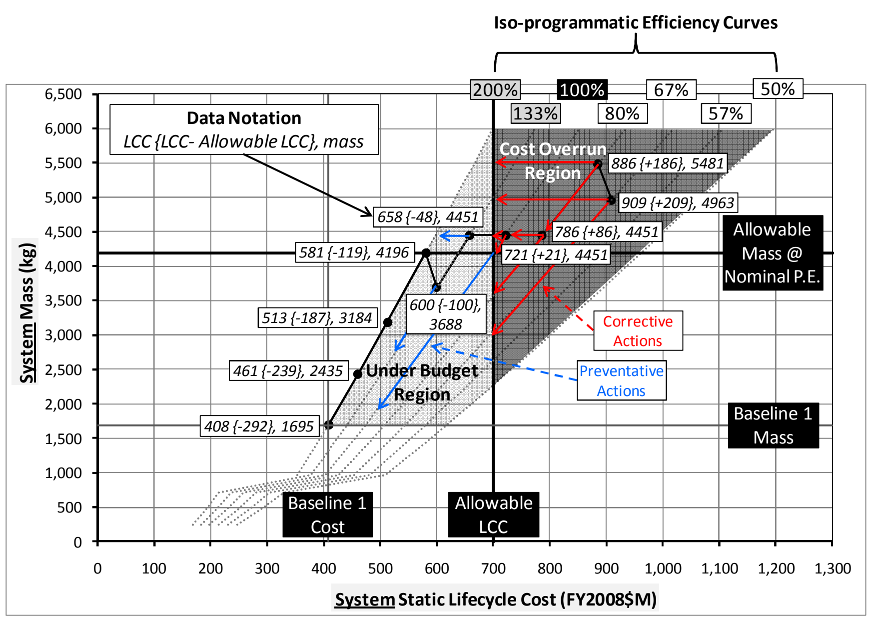

Figure 6. Monolithic Spacecraft Solution Space Relative to the Budget.

[3] Figure 6, 7, and 8 were generated, in part, through a linear interpolation the discrete solution space shown in Figure 5.

relative to the budget and the estimated spacecraft (program) mass, lifecycle cost, and programmatic efficiency, a set of preventative or corrective actions may be developed to avoid or mitigate growth in the spacecraft program cost after time T_i. On the basis of the potential solution space path and budget shown in Figure 6, potential preventative and correction actions are depicted as arrows in the figure. These actions may entail a reduction in the spacecraft mass or increase in programmatic efficiency to reduce the lifecycle cost of the monolithic spacecraft considered in this case study moving forward from time T_i.

Figure 7 provides an interpretation of the solution space and budget represented in Figure 6 in which iso-cost curves are shown relative to the programmatic efficiency and mass of the spacecraft. Note, that in Figure 7, the iso-cost curves quantify the estimated lifecycle cost of the spacecraft at a given mass and programmatic efficiency. In this sense, Figure 7 provides a visually different construct for developing cost growth avoidance and mitigation strategies, namely, from a constant-cost perspective. Using Figure 7, one can readily develop spacecraft (program) cost growth avoidance and mitigation strategies along constant lifecycle cost lines; hopefully, such that an amenable solution for the program between spacecraft mass and programmatic efficiency is reached.

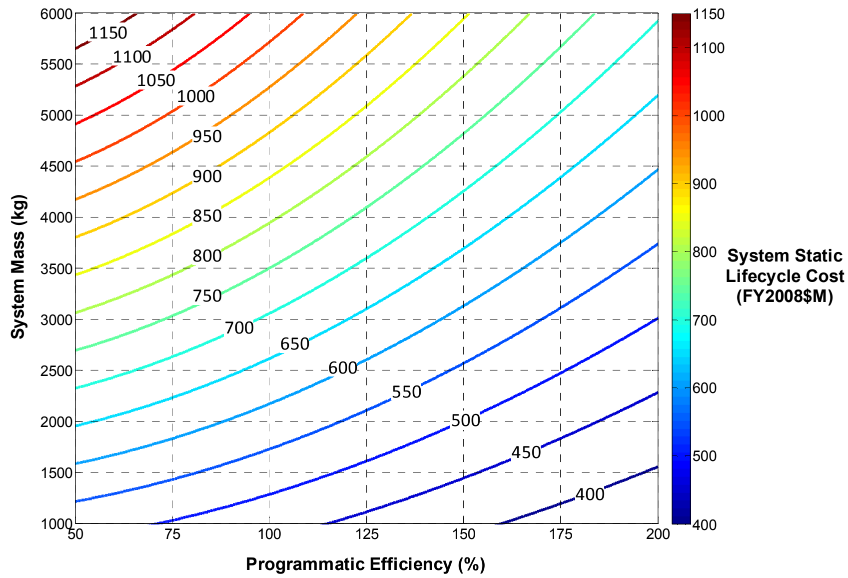

Figure 7. Monolithic Spacecraft Solution Space: Iso-cost Curves.

Analogous to Figure 7, Figure 8 provides another interpretation of the solution space shown in Figure 6. The three axes in Figure 8 characterize the respective lifecycle cost, mass, and programmatic efficiency estimate for each potential candidate spacecraft (program) in the solution space. This three-dimensional representation thus leads to the creation of a solution *surface*. The shading of this surface is based on the lifecycle cost disparity of a given spacecraft (program); the lifecycle cost disparity is the difference between the estimated lifecycle cost and the allowable program budget (*i.e.,* 700 FY2008$M). Hence, as the mass and programmatic efficiency increase, the closer the surface shade will reflect be to the red portion of the electromagnetic spectrum.

The motivation for using a solution surface such as that shown in Figure 8 is that it provides four dimensions of information to assist in developing cost-growth avoidance and mitigation strategies. Additionally, the solution surface can be used just as response surfaces are in multi-disciplinary optimization; this meaning that the response surface is used for real-time decision-making regarding the system interest, as the surface already enumerates all potential (desirable) solutions (Hosder et al., 2001). In this sense, the

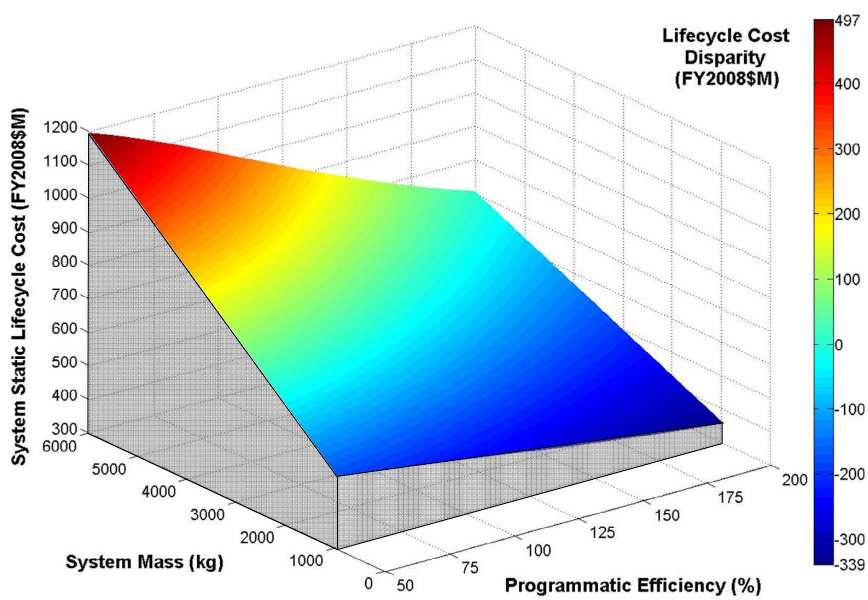

Figure 8. Monolithic Spacecraft Solution Space: Cost Disparity Gradient.

solution surface provides a holistic representation of the system along four dimensions, which can be used to develop preventative and corrective actions for avoiding and mitigating cost growth in real-time, provided that these decisions are made at time T_i. It is apparent, however, that the solution surface in Figure 8 is not immediately constructive for making specific decisions along the dimensions lifecycle cost, mass, and programmatic efficiency, since the surface is not trivial to visually navigate. The caveat to this is that the solution surface, since it is a single plane in three dimensions, can actually be represented as a numerical equation of three variables: (1) lifecycle cost, (2) mass, and (3) programmatic efficiency; thereby making specific tradeoffs immediately calculable. (The lifecycle cost disparity could be readily ascertained from this equation by taking the difference between the estimated spacecraft cost and the allowable program budget.). If a solution space can be characterized by a single equation of the *n* independent variables, then it provides an extremely valuable tool for making decisions to avoid cost overruns.

G. Generate Subsystem-Level Solution Space

Analogous the process used to generate the spacecraft program solution space at the system-level, one can generate a set of subsystem-level spaces, which characterize the respective subsystems found in each candidate spacecraft architectures present in the system-level solution space. As elude to in Figure 9, the system-level solution space shown in Figures 5 can be decomposed to the subsystem level, thus providing solutions spaces for each of the monolithic spacecraft subsystems listed in Section C. The motivation for generating the various spacecraft subsystem-level spaces is that the specific cost-growth avoidance and mitigation strategies (*i.e.,* preventative and corrective actions) developed at the system-level can directly prescribe cost growth avoidance and mitigation strategies for each of the respective subsystems in the spacecraft. In this sense, the subsystem solution spaces represent a decomposition of the system-level cost growth avoidance and mitigation strategies, which will subsequently better enable program managers to readily allocate mass and cost budgets within the (subsystem) design teams in a given spacecraft development program.

Generating the solution spaces at the subsystem-level is identical to generating solution spaces at the system-level. For a given spacecraft (program), the subsystem solution spaces can be created by simply decomposing and representing the spacecraft by its respective subsystems. The caveat to generating the subsystem solution spaces is that one of the *n* dimensions used to represent the space needs to be a system-level metric, as this will allow decisions made in the system-level domain to be accurately mapped to each respective constituent of the subsystem domain. For this particular case study, subsystem-level solution spaces were generated for the monolithic spacecraft subsystems enumerated in Section C. Note that one can readily develop cost growth avoidance and mitigation strategies at the subsystem-level, which can then be mapped to, and thereby drive cost growth strategies at, the system-level; this in turn being especially important for spacecraft with technologically volatile subsystems or payloads.

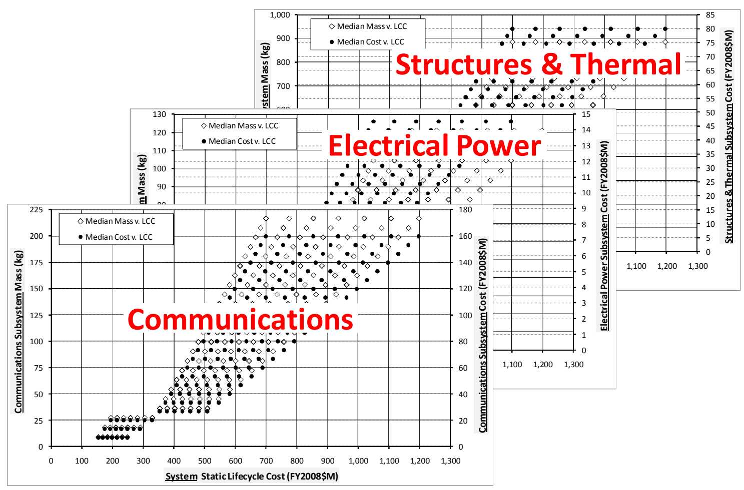

Figure 9. Monolithic Spacecraft Subsystem Solution Spaces.

VI. Discussion

The discussion of the methodology developed through this research effort is incomplete without noting the inherent limitations of, and contributions provided by, the methodology. However, regardless of these limitations and contributions, the research methodology does yield insights that can lead to the avoidance and mitigation of cost growth in spacecraft acquisition programs, especially during the early stages of the program lifecycle; this in turn being the point in which the majority of a program's cost is committed (Fabrycky & Blanchard, 1991).

The prescriptive cost growth avoidance and mitigation methodology presented and demonstrated herein has several notable limitations. The first of these is that the methodology will likely take more time to execute than other methodologies addressing cost growth in spacecraft acquisition programs, which rely on analogies to historical spacecraft. In this research methodology, generating the solution spaces, which are required to develop cost growth avoidance and mitigation strategies, is not a trivial process, depending on the time in a spacecraft program in which these solution spaces are generated. As a subsequent result, this research methodology may provide the most utility to a program manager during the early stages of a program when the solution spaces can be generated in a time-efficient manner. The second limitation of this research methodology, which is subsequently shared by all other methodologies addressing spacecraft cost growth, is that it provides no guarantee that cost overruns will not occur in a given spacecraft acquisition program. To mitigate this limitation, this research methodology emphasizes the continual provision of prescriptions for avoiding cost growth, rather than assigning a single percentage probability of completion value, or "lump sum" increase to the cost of given spacecraft program, as many other cost growth methodologies do. Depending on how active one wants to be in stemming cost growth in a given spacecraft acquisition program, these percentage probability and "lump sum" cost growth assignments are likely inadequate due to their entirely non-descriptive nature of the actual sources of cost growth in a program.

The remaining foreseen limitation of this research methodology arises from a situation in which, at a given time in a program lifecycle, the budget is not sufficient to avoid cost overruns; sometimes this reality is all but unavoidable given an organization's limited resources. If this is the case, this research methodology would show that corrective actions need to occur to reduce the budget of the program, however, in reality these corrective actions would need to be retroactive to actually reduce the program cost to an amount below its respective budget. This last limitation, which cannot be controlled by this or any other methodology addressing cost growth in spacecraft acquisition programs, provides the exact motivation for allocating system budgets (reserves) actively throughout the lifecycle of the program. It is therefore of most importance, in terms of avoiding cost growth, to quantitatively understand what and how much should be budgeted as well as providing a means for effectively managing the budgets such that the relationship between all budgets at the system, subsystem, etc.-level can be known accurately and readily over the lifecycle of a program. This last point happens to enumerate an especially important attribute of this research methodology, which is its provision of information to allow such budgets to be made and effectively managed over a program lifecycle, far better so than such provisions made by any other cost growth methodology.

The prescriptive cost growth avoidance and mitigation methodology presented and demonstrated herein provides several unique contributions to the field of cost growth assessment. The first of these contributions originates from the radically different philosophy of spacecraft cost growth adopted by this research, which leads to the methodology from inheriting the assumption made by the most prominent cost growth methodologies: cost growth in spacecraft acquisition programs can be appropriately addressed through comparison to historical spacecraft programs (*i.e.,* by analogy). Another contribution of this research methodology is that it provides a manner to potentially avoid but, at the very least, mitigate cost growth in an unconstrained manner by encouraging individual creativity as a means for populating and carrying out the constituents of the methodology represented in Figure 1. This latter point assuredly increases the applicability to the methodology to other system acquisition and program domains. To this end, the methodology is repeatable and extensible to any system (or program) with respect to any metrics characterizing that system, one need not be constrained to the four metrics found in the case study herein.

The remaining contribution of this research methodology builds on the previously mentioned contribution which is that this methodology avoids the crucial limitation possessed all cost growth methodologies relying on analogies to historical spacecraft programs, in any capacity. This contribution serves as a pivotal source of differentiation for this research and subsequent methodology, since it is not tied to the assumption that appropriate historical analogies to the spacecraft acquisition program of interest always exist. Therefore, this research methodology is the sole cost growth methodology that can be used to *appropriately* avoid and mitigate cost growth in acquisition programs for highly innovative (and even unprecedented) spacecraft acquisition programs.

VII. Conclusion

The methodology developed and demonstrated through this research effort offers a unique prescriptive approach for avoiding and mitigating cost growth in spacecraft acquisition programs, which is applicable over the entirety of a program lifecycle. Subsequently, this research methodology is philosophically different from all other cost growth methodologies because of its *prescriptive* nature. However, it is important to recognize that despite this research methodology's uniqueness, it achieves the same fundamental objective of all cost growth methodologies, which is a reduction in the probability that a spacecraft acquisition program will experience cost growth. And, as mentioned previously, while there are notable contributions made through this research methodology, there are also important limitations to be observed. Therefore, it is in recognizing both these contributions and limitations that one comes to understand the complementary, rather than competitive nature of this research methodology with other methodologies addressing cost growth in spacecraft programs. As such, the best prescription for avoiding and mitigating cost growth in spacecraft acquisition programs will come from an educated confluence of recommendations put forth by multiple cost growth methodologies, including this one.

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