Project Management using Modern Guidance, Navigation and Control Theory

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Abstract—Implementing guidance, navigation, and control (GN&C) theory principles and applying them to the human element of project management and control is not a new concept. As both the literature on the subject and the real-world applications are neither readily available nor comprehensive with regard to how such principles might be applied, this paper has been written to educate the project manager on the "laws of physics" of his or her project (not to teach a GN&C engineer how to become a project manager) and to provide an intuitive, mathematical explanation as to the control and behavior of projects. This paper will also address how the fundamental principles of modern GN&C were applied to the National Aeronautics and Space Administration's (NASA) Constellation Program (CxP) space suit project, ensuring the project was managed within cost, schedule, and budget.[1, 2]

A project that is akin to a physical system can be modeled and managed using the same over arching principles of GN&C that would be used if that project were a complex vehicle, a complex system(s), or complex software with time-varying processes (at times nonlinear) containing multiple data inputs of varying accuracy and a range of operating points. The classic GN&C theory approach could thus be applied to small, well-defined projects; yet when working with larger, multiyear projects necessitating multiple organizational structures, numerous external influences, and a multitude of diverse resources, modern GN&C principles are required to model and manage the project.

The fundamental principles of a GN&C system incorporate these basic concepts: State, Behavior, Feedback Control, Navigation, Guidance and Planning Logic systems. The *State* of a system defines the aspects of the system that can change over time; e.g., position, velocity, acceleration, coordinate-based attitude, and temperature, etc. The *Behavior* of the system focuses more on what changes are possible within the system; this is denoted in the state of the system. The *behavior* of a system, as captured in the system modeling, when properly done will aid in accurately predicting future system performance. The Feedback *Control* system understands the state and behavior of the system and uses *feedback* to adjust control inputs into the system. The *feedback*, which is the right arm of the *Control* system, allows change to be affected in the overall system; it therefore is important to not only correctly identify the system feedback inputs, but also the system response to the feedback inputs. The *Navigation* system takes multiple data inputs and based on *a priori* knowledge of the inputs, develops a statistically based weighting of the inputs and measurements to determine the system's state. *Guidance and Planning Logic* of the system, complete with an understanding of where the system is (provided by the *Navigation* system), will in turn determine where the system needs to be and how to get it there. With any system/project, it is critical that the objective of the system/project be clearly defined – not only to plan but to measure performance and to aid in guiding the system or the project.

The system principles discussed above, which can be and have been applied to the current CxP space suit development project, can also be mapped to real-world constituents, thus allowing project managers to apply systems theories that are well defined in engineering and mathematics to a discipline (i.e., Project Management) that historically has been based in personal experience and intuition. This mapping of GN&C theory to Project Management will, in turn, permit a direct, methodical approach to Project Management, planning and control providing a tool to help predict (and guide) performance and an understanding of the project constraints, how the project can be controlled, and the impacts to external influences and inputs. This approach, to a project manager, flows down to the three bottom-line variables of cost, schedule, and scope and to the needed control of these three variables to successfully perform and complete a project.

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[2] IEEEAC paper #1694, Version 4, submitted December 22, 2010.

1. INTRODUCTION TO PROJECT MANAGEMENT

Why Is Project Management Important?

Project Management is one of many fields that has evolved over the years from largely a management of labor, to a coordination of subcontractor labor and in recent years to an integration with other projects and programs while also maintaining requirements configuration management, schedule, budget, scope of work, etc. As the magnitude of projects and programs has grown in size and complexity along with the financial and schedule pressures, so too, has the need to develop tools and best practices to provide a better posture for successful completion.

History of Project Management

"Managing projects is one of the oldest and most respected accomplishments of mankind. One stands in awe of the achievements of the builders of the pyramids, the architects of the ancient cities, the masons and the craftsmen of the great cathedrals and mosques, and of the might of the labor behind the Great Wall of China and other wonders of the world. People were riveted at the sight of the Americans landing on the moon. All of these endeavors are projects, like many thousands of similar task-oriented activities, yet the skills employed in managing projects, whether major ones such as those mentioned above or more commonplace ones, are not well known other than to the specialists concerned." [1] While it is probably not healthy for project managers to individually view themselves and their job importance in such terms as these, it is worth noting that without the skills and insight to lead projects – large or small – to completion, none of these achievements would have been realized. The art of Project Management across the ages has been achieved through the innate skill of those leading the tasks via intuition and empirical observations of what worked and what did not. In recent years, however, it has been recognized that there are common traits to projects, tools, and methods that can be used to manage the projects and best practices to follow.

What is the State of the Art in Project Management?

The best practices and tools available to project managers have evolved and become quite sophisticated. Today we can characterize the state of the art for Project Management best practices to be counted among the ranks of the standards of the Project Management Institute (PMI),[3] which issues Project Management Professional (PMP) certification credentials to individuals who are practicing the art of Project Management[4]. Similarly, the tools for performing Project Management have evolved over time and developed into math-based theories based on the statistics of the project metrics to assess the health, status, progress, and likely end-of-project triad of cost, schedule, and scope. Such tools include detailed, resource-loaded schedules tied to work breakdown structures that are cross coupled with budgets, charge codes, labor distributions, organizational breakdowns, and earned value metrics that weigh the relative relationships of the project metrics to assess the status and health of the project-based equations that were formulated from consistent historical observations.

There are statistical tools, known as probabilistic risk assessments (PRAs), that are typically used to get a realistic look into the future using statistical likelihoods that are based on previously completed, relevant, programs and projects in which the final project metrics are used to estimate the project in question. While PRAs are usually used during project formulation to help bound the project and obtain the first realistic prediction of project life-cycle cost based upon desired confidence levels, PRAs can also be used midcourse in a project to obtain a clearer forecast of the project's outcome given that more actual data is known of the project and some history exists from which to draw. However, it should be recognized that the usefulness of PRAs is limited to the independent historical project data they draw from and the relevance to the current project in question. Not all PRA tools are created equal or with the same *a priori* knowledge. It has been the author's experience with using PRAs at NASA [2] that they are useful as a thumbnail estimate, but that most of the PRA tools available are based upon commercial or military aviation projects. While these tools are somewhat similar in nature, the complexities, risks, and shear quantities are of completely different magnitudes when compared to human space programs during the last 50 years, the number of which can be counted on one hand. So, it is for the smart reader to read the fine print of the PRAs and use as appropriate.

While Project Management best practices, surveillance, and prediction tools have been making headway in recent years, our fundamental understanding of the dynamics of projects has not. To achieve some perspective, it should first be noted that all physical systems in our universe follow fundamental laws of physics that can be characterized by equations down to the quantum level. This means that once we have the equations that fully characterize a physical system, we can predict the outcome of given input to that system with very high probability and accuracy. This has not been possible in many areas of our lives, such as weather forecasts made more than four days in advance, global warming, and the stock market, but this is more of a limitation of computational capacity to test mathematical relationships, and consequently the observablity of the systems, than an ability to formulate correct equations. To that end, as the physical systems on Earth have evolved and become more complex in terms of life forms, the number of uncertainties, dependencies, and mathematical variables has grown beyond our computational capabilities.

An interesting phenomena takes place where the understanding of the sum of individual interactions between the

[3] The author has no affiliation to this organization and is not promoting such certification, but provides this as one such industry-accepted approach to education and certification of Project Management training.

[4] Project Management is not yet a science; therefore, like most highly tuned skills, masterful Project Management is considered an art.

system constituents not only is currently computationally impossible but has only a third- or fourth-order effect on the system behavior as a whole. For example, does the semi-random motion of white blood cells affect how one's body might move, where the body goes, or what one does during any given day? No, of course not; yet although at some level it is important how the cells work, it is less important how they affect one's daily motion. This brings into the picture the idea of understanding the system of constituents as a whole. This concept is not new, as scientists have long observed the phenomenon of the dynamic motion of schools of fish, flocks of birds, colonies of bees and ants, and large herds of land mammals. So, the author asks, "Why has this not been applied to the dynamics of a group of people working together, in some association with one another to achieve some agreed ends to their efforts?" This sounds a lot like a project in which a project manager would like to understand how it behaves (macroscopically) so that he or she can better understand how to manage it and come to a successful conclusion. Moreover, this also resembles physical systems for which the engineering world has developed highly sophisticated mathematics and models to not only understand the systems but to control them. It is this application of engineering principles to human systems that will better provide a physical understanding of how projects respond to input and how best to guide and control, i.e. to manage, the outcome of the system.

2. APPLICATION OF MODERN GUIDANCE, NAVIGATION, AND CONTROL (GN&C) PRINCIPLES TO PROJECT MANAGEMENT

What Is Modern GN&C?

Modeling a system as a block diagram aids in understand the components of that system, its inputs, and its dynamics. For the discussions here, given the complex nature of the projects necessitating the application of modern GN&C and multivariable control system theory, a generalized, closed-looped system will be used. Such a system block diagram, which would look at a high-level like the one in Figure 1, is comprised of the system dynamic model, comparison function, controller, process, measurements, disturbances, and system response. A more detailed diagram showing just the Guidance, Navigation, or Control blocks is not provided since actual implementation of the functions can be variable and at the discretion of the engineer. This paper will focus on the functionality and how it will integrate at the system level.

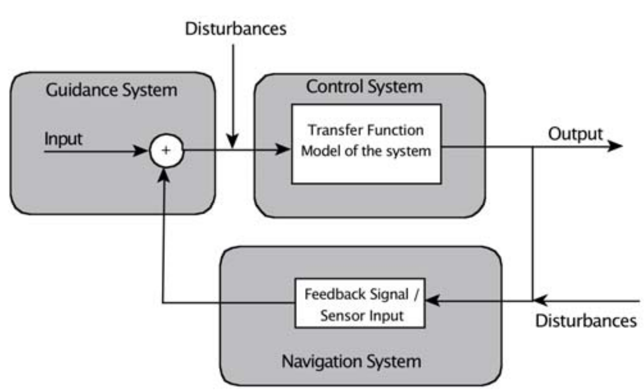

Figure 1 – A generalized block model of a vehicle system showing the Guidance, Control, and Feedback systems.

Open- vs. Closed-loop Systems

Open-loop models work well for simple or well-understood systems such that the actual output of the system is as desired without feedback; e.g., a factory stamping out metal washers: the metal feedstock goes in, is stamped and the washers come out good enough without a need for a real-time adaptive system.

A closed-loop system uses an analysis of the actual system response to a system control input to determine control performance of a system that may not be completely understood or be able to be effectively modeled mathematically.

History of GN&C

The history of GN&C, why it has been critical in engineering over the last 40 years, and why it is important to understand for large projects of today is a relatively new idea. But, before one can understand the relationship and appreciate the applicability to projects, it is first necessary to understand the impact of GN&C theory to the engineering world.

"The origin of the terminology causes some confusion, particularly when reading older sources or reference not associated with satellites. *Navigation* traditionally referred to determining how to get a craft where we wanted it to go. The term *guidance* was introduced with rockets and missiles to mean computing the steering commands needed to make the rocket go where we wanted it to (thus, a *guided* missile); *control* meant carrying out these steering command to adjust the vehicle's direction of flight. Thus, an intercept missile would have a *guidance and control (G&C)* system and a space plane or [an] interplanetary spacecraft would have a *guidance, navigation, and control (GN&C)* system. However, for spacecraft we use *navigation* to mean orbit determination, *guidance* to mean orbit control, and *control system* as a shortened form of attitude control system." [3]

To add some levity while yet explaining the fundamental principles of GN&C and recognizing that what is said is fundamentally accurate, we will provide the script for an early GN&C educational video that is widely known in the GN&C industry as a source of humor due to its seemingly obfuscated explanation of missile GN&C systems.

> *"The missile knows were it is at all times. It knows this because it knows where it isn't. By subtracting where it is from where it isn't, or where it isn't from where it is – whichever is greater – it obtains a difference, or deviation. The guidance subsystem uses deviation to gen-*

erate corrective commands to drive the missile from a position from where it is, to a position where it isn't and arriving at a position where it wasn't, it now is. Consequently, the position where it is, is now the position that it wasn't and it follows that the position that it was, is now the position that it isn't. In the event that the position it is in is not the position that it wasn't, the system has acquired a variation. The variation being the difference between where the missile is and where it wasn't. If variation is considered to be a significant factor, it too may be corrected by the GEA. However, the missile must also know where it was. The missile guidance computer scenario works as follows: Because the variation has modified some of the information the missile has obtained, [the missile] is not sure just where it is. However, it is sure where it isn't, within reason. And, it knows where it was. It now subtracts where it should be from where it wasn't, or vice versa. And, by differentiating this from the algebraic sum of where it shouldn't be and where it was, it is able to obtain the deviation and its variation, which is called error." – author unknown

While this can be a bit hard to follow and needs to be read a few times, it illustrates that getting from point A to point B requires the knowledge of where one is, where one wants to be, what is needed to get there and the importance of having a model for estimation and prediction.

Why Is It Important?

For the uninitiated it may be unclear why one might need to implement or even understand GN&C theory. To illustrate the value of this understanding and when it should be applied, the following analogy is provided: Take the everyday wheelbarrow, one uses it to hold the material placed into it and to move the contents under their generally graceful control to some predetermined location. In that situation, the system is comprised of an operator, the dirt, and the wheelbarrow. Things are pretty intuitive and well controlled and have a well-defined understanding of where the dirt is at any given time and where ultimately the location is to which one's spouse instructed it to be delivered. Now to make this somewhat more interesting, it is requested that one place a front-loader on the wheelbarrow that will self-load the dirt and a motor so the barrow can move under its own power. It is also requested that the dirt be removed from the front yard and delivered to the operator's mother-in-law's flower bed that is across town, that delivery be operated via remote control ... at night. At this point, the reader can appreciate how much more complicated the task at hand has become, how much more complicated controlling this "system" to accomplish the task will be, how important it is to be able to know where the system is at any given moment, and how far off the system is from the desired destination. So, too, is the appropriate implementation of GN&C principles to Project Management, understanding the physical behavior of the system and how to control it.

How Does It Apply to Project Management?

Much of what has been written about Project Management in the last 30 years has primarily focused on the evolution of tools, which have proven to aid in the predictability of the outcome of projects. However, little has been done to characterize the discipline in terms of physical or mathematical models or system characterization; i.e. system dynamics. This lack of mathematical modeling has largely been due to the extreme difficulty met in being able to model human behavior and decision processes in terms of generalized equations, and is also due to the lack of the proper mathematical reference within which to frame the problem.

To date, our ability to predict human behavior has only been possible through statistical analysis of outcomes of human behavior and performance. And to that end, human behavior and performance can be modeled in terms of bell-curve distributions [4] – whether in performance in running a mile or education [5], performance and fatigue while under stress, human performance and associated behavior, it is fairly predictable in this context. While some aspects of how this performance modeling has been applied to specific individual predicted performance (ranging from the relationships between low measured intelligence and anti-social behavior and genetic factors in intelligence abilities [6]) are still under debate, the theory itself has shown to track quite well as to many aspects of human performance. Significant understanding of human decision-making processes at the neural level have been made in recent years in artificial intelligence research [7], but human decisions are still largely bound by personal experience, values, specific real-time environmental drivers, individual brain chemistry, and neural firings whose outcomes are practically limited by Heisenberg uncertainty[5]. So, given these variables along with the computational demand of what would be required to predict a project's outcome, factoring in the human element, for hundreds – if not thousands – of individuals, it is not currently a practical approach to project management and forecasting.

In much the same vein of understanding that weather does not rely on modeling the dynamic motion of each atom or molecule in the atmosphere, by looking at the problem in terms of *systems-of-systems* it is possible to see and understand the predicable and quantifiable dynamic equations of motions for a system. In this approach it is possible to treat a system-of-systems comprised of humans rather than mechanical components, individual machines, or computer processors. And, given a statistical understanding of human performance, it is now possible to model the "dynamics" and performance of the system to greater accuracy. It is

[5] Human decisions are based on neural-chemical interactions between the neurons in the brain, and the outcomes of these electrochemical reactions are what drive the higher-level brain response and subsequent decisions or physical responses. Therefore, at the core of Werner Heisenberg's Uncertainty Principle is the fact that many decisions have their fundamental genesis in how molecules interact – driven by interactions of electrons – and our inability to measure or predict the outcome of such interactions without disturbing the state of the system.

therefore possible to define a project or program, based on our assumption of a system-of-systems consisting of humans, and to begin to model the dynamic equations of motion, the data required to understand the state of the system, the variables that are important to the control of the system, and our ability to guide the system to the desired stated of completion.

3. PROJECT NAVIGATION

What Is Navigation, and How Is It Used?

Navigation "measure[s] position from a fixed point of reference (ex. landmark, north star, beacon), relative position to a target (ex. radar, infrared, ...), [and/]or track movement from a known position/starting point." [8]

Modern GN&C uses many different methods of gathering the system navigational state vector[6] via an assemblage of sensor suites. And, following the path expressed by the previous wheelbarrow example, the GN&C system takes the information of where it is and determines whether it is where it needs to be. A significant portion of what the navigation systems does is to understand where it is and the accuracy of the sensor data. A fundamental part of modern navigation computing is the use of the Kalman[7] filers that employ measurements observed over time that contain noise (random variations) and other inaccuracies and produce values that are closer to the true values of the state vector by statistical *a priori* knowledge of sensor performance (expected error) and of the correlation of state vector variables [9]. Great strides have been made in augmenting navigation system performance and robustness in the area of artificial neural networks in recent years. These neural networks can be implemented in many ways – from determining which *a prior* model of the environment matches current vehicle performance, to banks of simplified Kalman filters [10], to artificial neural networks on distributed processors that detect failing sensors which are no longer providing sufficient information for the current flight regime [11]. While this marriage of statistical estimation and neural-network decision making is still in a relative infancy as compared to human ability to observe, determine the validity of data, and make judgments, it none the less defines the state-of-the-art in navigational computing.

Applications to Project Management Navigation

Knowing where you want to be in many of our project lives is a process of continuous, strategic reacquisition of targets due to a rapid or continuously changing economic or political environment. In such situations, knowing exactly the sate your project is critical for your project's survival. It is important to know what information is needed to effectively understand where the system/project currently resides. In the Project Management world, this is known as the project metrics. And understanding the statistical significance (or accuracy) and latency (how old is the information and is it of importance to the project) of the information received is also related to determining the necessary project metrics.

Tools: Sources of System Data/Project Metrics

In vehicle design terms, the ability of the navigation system to understand and determine where the system is located is dependent on the sources of information. In terms of Project Management, the major advances in the theory and best practices over the last few decades have been in the development of processes and tools to provide better insight into the health and status of the project. Or, in other words, "Are we where we want to be? If not, how far off are we? And how reliable and timely are my project metrics?"

As discussed earlier, it is important to have the appropriate information to determine the status and progress of a project and such tools as Gantt charts, critical paths, resource-loaded schedules, earned value management (EVM), full-cost accounting, known risks, and mitigation plans, to name a few, are all examples of recent advances in determination of what information is typically most useful to understand the state of the project (in engineering terms, the state vector of the system). On the "softer side" of Project Management, important project metrics are: team morale and relevant local, national, and international news.

(1) Gantt Charts—Henry Laurence Gantt (1861–1919) was a mechanical engineer, a management consultant, and an industry advisor. He developed Gantt charts in the second decade of the 20th century as a visual tool to show scheduled and actual progress of projects. Accepted as a commonplace Project Management tool today, it was quite a radical concept and an innovation of worldwide importance in the 1920s. Gantt charts were first used on large construction projects such as the Hoover Dam, the construction of which started in 1931, and the US interstate highway network, the construction of which started in 1956. [13]

(2) Resource-loaded Schedules—were developed to better predict the required resources and task durations to a low-level resolution at the beginning of a project to help avoid gross misestimations on the life-cycle cost of the project. And, depending on the size of the project, they can be a useful tool to keep a real-time knowledge of the end-of-project cost estimates or can be used to make very informed, real-time scope vs. resources vs. project schedule decisions. However, as has been seen time and time again, the larger the

[6] For vehicles, either controlled directly by humans or autonomously, typical state vector variables consist of the position, velocity, acceleration and time at which the measurements were taken. This information is also measured for aeronautical or space faring systems or for systems that require the relative attitude of the vehicle.

[7] In 1960, R.E. Kalman published his famous paper describing a recursive solution to the discrete-data linear filtering problem. Since that time, due in large part to advances in digital computing, the Kalman filter has been the subject of extensive research and application, particularly in the area of autonomous or assisted navigation. [12]

project, the larger the standing army that is required to feed and maintain a detailed resource-loaded schedule.

(3) EVM—The genesis of EVM, which occurred in industrial manufacturing at the turn of the 20th century, was based mostly on the principle of "earned time" popularized by Frank and Lillian Gilbreth, but the concept took root with the DuPont Corporation and General Dynamics in the 1950s and later in the US Department of Defense in the 1960s. The original concept was called PERT/CSCSC [program evaluation and review technique/cost schedule control system criteria], but it was considered overly burdensome (not very adaptable) by contractors who were mandated to use it, and many variations of it began to proliferate among various procurement programs. EVM is able to combine performance measurement and management tools that integrate technical (progress on scope of work), cost (actuals tracked by work breakout structure [WBS]), and schedule parameters (milestones as a measure of the earned value of the scope of work completed) of a contract. [14]

(4) Risks and Mitigation Status—The fundamentals of risk management are centered on quantifying any potential risks that might affect a project, identifying the consequence if a risk occurs vs. its likelihood to occur, and the plan to mitigate the risk to a manageable level. Understanding risks to a project and actively managing those with the greatest threats are critical to avoiding any unforeseen (did not bother to look around and see the hungry tiger) or ignored (proverbial ostrich risk management approach) risks. [20]

(5) Morale of the Team—Maintaining an accurate reading on the morale of a team is critical to the success of the project and the project manager. Team morale can be affected and shaped by not only the direct actions of the project manager but by peer influences, news from the outside, and perceptions of both the present and the future. Team morale can also be influenced by the type of work being asked of the team's members, the pace at which they are expected to perform, whether they feel the work is meaningful, and whether they are fairly compensated for their labors. All of these factors will influence individual performance and, ultimately, the performance and productivity of the team as a whole. This, therefore, is one of the critical project performance inputs that is required to effectively manage a project and can only truly be obtained by personal relationships with the team and by "managing by walking around" (MBWA)[8] and talking to people.

(6) The News and Trusted Sources of Information—Team, corporate, industry, local, national, and world news all can be very important project control inputs influencing anything from previously mentioned team morale to project risks (technical, scope, financial, etc.), to funding possibilities, or to sales growth potentials, to name a few. Much as a systematic approach was taken to identify the risks to the project, the same diligence should be taken to understand the influential information and received updates in a timely fashion for the project. As discussed later in the Project Control section, the timeliness of project input into the system from outside is just as important to project performance as the timeliness and frequency with which project corrective inputs are made by the project manager. For example, not consulting the stock market trends and futures on advanced technology before committing significant project or company resources can be a recipe for disaster, just as would be committing a standing army to launch the space shuttle while not consulting the long-range weather forecast and not knowing a hurricane was bearing down on Florida. While there is little protection against the "unknown unknowns" out there, without a reliable crystal ball, some amount of effort can reduce many surprises in a project's life.

4. Project Guidance

What Is Guidance, and How Is It used?

The *guidance system* in the engineering world is sometimes at best hard to distinguish from the navigation system due to tightly correlated functions and how they are implemented in the final design. However, from a theoretical and an engineering discipline perspective, the two systems are very different, and guidance theory can best be described in terms of implementation in a flight vehicle as:

> "Guidance [system], which leverages navigation data and target information to direct flight control 'where to go'. Guidance is the 'driver' of a vehicle. It takes input from the navigation system (where am I?) and uses targeting information (where do I want to go?) to send signals to the flight control system that will allow the vehicle to reach its destination (within the operating constraints of the vehicle). The 'targets' for guidance systems are one or more state vectors (position and velocity) and can be inertial or relative. During powered flight, guidance is continually calculating steering directions for flight control. For example the space shuttle targets an altitude, velocity vector, and gamma to drive main engine cut off." [8]

All of the guidance tools available at a project manager's disposal are to drive down the delta in project status, as determined by navigation function, and to calculate what needs to be done to get the project on a corrected course to

[8] Dave Packard and Bill Hewlett, in the early days of Hewlett-Packard, devised an active management style that they called MBWA in which senior managers were seldom at their desks and spent most of their days visiting employees, customers, and suppliers. The MBWA concept was popularized in 1985 by a book by Tom Peters and Nancy Austin. Japanese managers employ a similar system, which originated at Honda, and is sometimes called the 3 Gs (*genba*, *genbutsu*, and *genjitsu*, which translate into "actual place," "actual thing," and "actual situation"). [15]

reach final programmatic goals. An ability to predict the future and to have a state vector and accurately integrate it forward in time is critical so that accurate guidance can be formulated and applied.

Fault Tolerance – What Happens If You're Not Omniscient?

Even in the world of engineering, protecting the system from the unknown unknowns out there has been slow and complicated to implement into practice: "Conventional GN&C brings a mature understanding of dynamics and statistical modeling, measurement and estimation, control, planning, optimization, and other design elements – in each case grounded in solid theoretical foundations. But fault tolerant GN&C has a different story to tell. Many lessons have been learned over many years and many projects (usually something like, 'Don't do that again'), but progress has been slow. Theoretical grounding for fault tolerance, as generally practiced, has significant ground to make up in comparison to its conventional cousin." [16] So, it is within Project Management and how the project is structured and controlled that we are able to tolerate and respond to the unknown unknowns that continually bombard our projects and are impossible to predict.

Rasmussen's words could not be more appropriate to the discussion at hand and the importance in addressing Project Management in this new way: "This is of particular interest now, because in many ways we have reached the end of an era, where it might be said that customary methods have been carried to their logical extreme. In fact, by some assessments, standard [fault-tolerant] design is in crisis, as the same litany of problems recurs on project after project (late delivery, fragile behavior, poor operability, incomplete testing, and so on) – and this is before considering the implications of new mission types that will push even harder. Solutions are not likely to come merely by polishing existing methods, starting them earlier, integrating them better, or wrapping them within tighter processes. The roots of the problem are deeper than this, so a different path is required." [16]

NASA has adopted and exercised many of the different principles of Project Management and control over the years from "build the hardware to get us there and we'll let the paperwork catch up" of the Apollo era, to the Constellation Program (CxP), which implemented full-cost accounting, EVM, ISO (International Organization for Standardization) practices, and rigorous systems engineering practices and models. However, in the final analysis the time or cost of the programs has not been significantly reduced, and it is the author's opinion that some of the principles are not conducive to implementation within government or have diametrically opposing goals with competing process implementations when implemented in a textbook fashion.

To cite a few examples: While textbook systems engineering principles and practices with detailed processes, requirements, documents, interface management, drawings, and working groups ensure all design decisions are compliant with requirements for the final product and a deliberate change management process, this method also does not lend itself to a project that must respond dynamically to changing requirements, requires rapid turn around in both design and prototyping, needs small and highly effective teams, or faces uncertain future funding; yet it is reinforced in an environment in which any failure is not tolerated. EVM, while also seemingly effective in the private sector as a management tool for projects for which funding has been budgeted and assured for completion of a project, is not the environment in which government programs live. Most government agencies and projects cannot be assured any funding past the current fiscal year boundary. Conforming to the best practices of EVM also requires a small standing army to feed the financial and resource-loaded scheduling tools that conflict with smaller budgets, small dynamic teams, or project schedules that outpace the ability of a team to input data into the systems.

The intent of this discussion is not to disparage some of the latest theories in Project Management best practices, only to emphasize three things: 1) Not all problems require a hammer; 2) If you only have a hammer, all of your problems look like nails; and 3) Situations will arise in which your system does not respond the way you expected and your tools are not providing the information you need. So to that end, we must engineer our projects to be fault tolerant to survive the unknown unknowns and provide guidance in situations in which our tools are either not providing the information we need or not providing it in a timely manner.

5. PROJECT CONTROL

What Is a Control System, and How Is It Used?

The following quote very well summarizes why the study of control theory and control systems is important in the world of engineering and also addresses the premise of this paper and the application to business and Project Management.

> "Control engineering is based on the foundation of feedback theory and linear systems analysis, and it integrates the concepts of network theory and communication theory. Therefore control engineering is not limited to any engineering discipline but is equally applicable for aeronautical, chemical, mechanical, environmental, civil, and electrical engineering, For example, a control system often includes electrical, mechanical, and chemical components. Furthermore, as the understanding of the dynamics of business, social, and political systems increases, the ability to control these systems will also increase." [17]

In theory, the vehicle control system will accept guidance commands (influenced by knowledge of the current state of the system as provided by the navigation system) to effect change in aerodynamic and/or engine controls. In managing a program or a project, the need to understand your end state or goal (the guidance system) while very important is only one of three legs to the GN&C stool. Knowing where you need to be (the project guidance system) based on project status and performance metrics (the project navigation system) now culminates in affecting change in the project based on input from the other two and knowledge of the physical response characteristic of your project. In terms of a physical system, using the knowledge of how the system responds to inputs (dynamic response due to the equations of motion), the system calculates the required inputs to command the system "effectors" to place it on a corrected course.

Control systems engineering activities, which are multidisciplinary in nature, focus on implementing control systems which are mainly derived by mathematical modeling of systems of a diverse range. The development of semi-/fully autonomous vehicles that largely self-regulate the system by adapting to environmental inputs into the system, unknown vehicle performance responses, and even new goal states is at the cutting edge of control system technology. Some examples of such systems are: self-tuning controllers if the process behavior changes are due to aging, drift, wear, etc.; adaptive controllers for nonlinear or time-varying processes; and adaptive or self-tuning control of multivariable controllers for multivariable processes (an example would be multiple input, multiple output [MIMO] systems).

Control systems are used to achieve efficiency and some level of automation to improve productivity and/or product quality or to obtain a desired level of automatic/autonomous control. As in the world of machines and vehicles, the need for dynamic change in a project control system as a response to a morphing project, its dynamics, inputs, weightings, size, etc., has to be able to change the project controls as the project changes to facilitate efficient system performance and product quality. Dorf and Bishop further illustrate this:

> "… it has become interesting and valuable to attempt to model the feedback processes prevalent in the social, economic, and political spheres. This approach is undeveloped at present but appears to have a reasonable future. Society, of course, is composed of many feedback systems and regulatory bodies, such as the Federal Reserve Board, which are controllers exerting the forces on society necessary to maintain a desired output." [17]

Open-loop vs. Closed-loop Project Control and

Likely Outcomes

Open-loop projects are subject to the gods of entropy and luck. They typically run unbounded or have managers who systemically overreact, causing negative input or "pumping" into the system resulting in an uncontrollable project and system collapse. Closed-looped systems have a feedback mechanism, which is a measure of the system's response to input, that allows further tweaking of system inputs to gain better control authority of the system or the project. Such a system does not guarantee a successful project, but it does increase the opportunities for success.

Defining the Project Control Variables

To define system/project control variables/inputs, we must gain knowledge of what the control inputs are to the project and when and to what degree input is required to get the desired effect via system output that is measured using project metrics. One example, borrowed heavily from the terminology of the GN&C modeling world, will be provided to illustrate how this would be applied mathematically to a

Figure 2 – A simplified system block diagram representing the different system aspects as linearized equations in the frequency domain.

project using a simplified version of Figure 2 (a simplified version of Figure 1) in which different parts of the project have been replaced with variables to help provide the next level of understanding of the system. The input variables, commonly from the guidance system, are represented by R(s), the output of the system by C(s); the feedback function by H(s) as performed by a sensor suit or Navigation system (depending on the complexity of the system), and the system's transfer function by G(s). Two important things to notice here are: first, the system transfer function, a mathematical model of the system dynamics, is typically in the form of simultaneous differential equations[9]. The system transfer function relates system inputs to system outputs. Second, the differential equations are generally difficult to work with when developing a control system and, therefore, are replaced with Laplace transformation equivalents that reduce the mathematics to a set of linear algebraic equations represented by the (s) notation. While it is not the scope of this paper to show how to model your project through a set of differential equations, it is worth noting how the generalized model is arranged and that you can begin observing how the input to your project impacts the output.

However, for a generalized model of a project, we will use the textbook example of a spring-mass-damper mechanical system. The time domain representation of this is system is:

$$F_{Total} = F_{oscillatory} + F_{damping} \qquad (1)$$

[9] Dynamic equations of motion that model real-world systems are a function of time, noted by (t). The movement of an object through space and time is how humans denote the change in a system's state or position.

where total force (F_{Total}) is equal to system oscillatory force ($F_{oscillatory}$) plus damping force ($F_{damping}$). The equation can be expanded to include system representation of the mass, springs, and dampers to

$$M\frac{d^2y(t)}{dt^2} + c\frac{dy(t)}{dt} + Ky(t) = 0 \qquad (2)$$

where: M = mass of the system
$y(t)$ = is the time-varying vertical displacement of the mass
c = is the dampening (friction) constant
K = is the spring constant

Equation 2 can be further simplified to

$$M\ddot{x} + c\dot{x} + Kx = 0 \qquad (3)$$

where: $\ddot{x}$ = system acceleration
$\dot{x}$ = system velocity
x = system position

Now dividing by the mass of the system and defining the following variable that models natural frequency of the system, ω_0, and the dampening coefficient, λ, we get

$$\ddot{x} + 2\lambda\omega_0\dot{x} + \omega_0^2 x = 0 \qquad (4)$$

where: $\lambda = \frac{c}{2\sqrt{MK}}$

$\omega_0 = \sqrt{\frac{K}{M}}$

Equation 4 can then be taken into the Laplace domain to solve for roots of the system that will characterize system stability. The full derivation of the differential equation solution can be seen in [17], but response to this system with varying dampening coefficient can be seen in Figure 3. When the dampening coefficient equals 1, we see the system quickly and smoothly approach the new system state given an input. If the coefficient is greater than 1, we see the new system take much longer to approach the new state, so it is considered *over-damped*. For systems that are considered *under-damped*, we see the coefficient is less than 1 and can oscillate to the point at which the system can fall apart or be uncontrollable.

The moral is to "Understand Your Dampening Coefficient of Your Project": If your system is under-damped – usually via poor or over-reactive leadership (leadership overreacts to events or team members do so, respectively) – your project will expend wasted resources, burn out people, or vibrate out of control and fall apart. If project leadership is too conservative, this can result in the project taking too long to reach a new and desired state for the project. And, in business terms, that could mean millions of dollars of lost revenue because the competition arrived at the solution first.

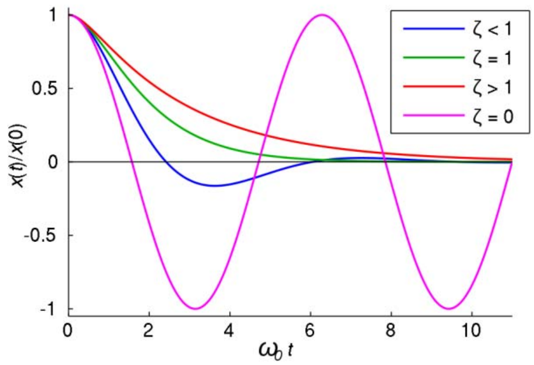

Figure 3 – Plot shows the system response to varying values of the dampening coefficient where $\zeta = \lambda$ is defined in the above figure.
Plot attribution: Created by a MATLAB script and provided by Nmnogueira at en.wikipedia

It is also important to understand how you can determine what your dampening coefficient is and what the constituents mean in terms of project control. Using equation 4, we see it in terms of current position, velocity, and acceleration of the team where the natural frequency, ω_0, is a function of spring constant (or natural dynamic of the project), K, and the mass, M, is the size of the project or team. And, the dampening coefficient, λ, is in terms of damping constant (or friction constant) and can be considered a summation of the resistive forces working against the team or decisions of the project manager. These resistive forces can be quantified in terms of schedule or dollars (one is a function of the other); impact due to disagreeable personalities; counterproductive policies, taxations, built-in process delays, project change control, fiscal uncertainty or change, etc. So, we can think of the dampening coefficient in total terms of the force of project resistance divided by two times the square root of the mass of project times project's natural dynamics. While this is a dimensionless ratio, the ratio does give more of an intuitive response to a project given a new input and a way to understand a project's response and areas to investigate for change that would allow tuning the project's dampening coefficient to produce a more desirable response to change – which in this case could be changing the size or the culture of the team.

Traditional Project Control Variables

Specific project control variables can change depending on the project, but traditional high-level control variables are (vehicle analogies in parentheses): resources (fuel), scope (vehicle functional capabilities or mission profile), project status and authority (attitude determination and control), and schedule (thrust, velocity, etc.).

One example of a method of a project control is *project change control*, which controls the time-based variable nature of the change in the system. Whether controlling the change in the project end state (e.g., configuration control of product requirements) or the time-varying equations of motion for the system (e.g., understanding and controlling how the project is structured and changes over time either through change control boards, deliberate organization restructuring, or new or changing customers and their inputs), this, too, should provide an emotional response to the experienced project manager who has worked on projects with too much change control for what the project required. The effect of this was a system that was over-constrained (over-damped), and it almost required an Act of Congress to get changes approved through the systems. Many have experienced the corollary in which there was insufficient project change control and significant amounts of lost productivity due to rework or a lack of configuration management – effectively resulting in an under-damped system. It is important to understand the correct amount of project change control for the system and to be able to use it to maximize productivity, which is not to be viewed as an impediment.

Control Authority

Control authority is the capability of the control system to overcome disturbance forces that are moving the system out of the desired trajectory. This paper will not go into derivations of the control authority of vehicles due to the specific and intrinsic dynamic equations of motion of vehicle effectors and the response to the system, but rather will provide an understanding in terms of Project Management. It is a project manager's ability or the project control functions – e.g., project change control, processes, procedures, etc. – that affect change of project direction or schedule. It is critical to understand early on whether the appropriate delegation of authority is in place to affect change, be it on an individual responsibility level or at a board or panel level.

Attitude Determination and Control

Attitude determination (provided by the navigation system) and control are dependent on the accuracy of attitude sensors and the control authority of your vehicle or project. While the equations of attitude torque (method to control external torques [adverse external inputs that steer a project in an undesirable direction] or used as a project steering function) will not be discussed here, they can be found in [3, p. 307]. Relating back to control authority, it is important to understand whether your project has the ability to affect a course correction due to external forces. An example may be having sufficient management budget reserves to counteract annual funding shortfalls, labor surge capability to address unknown issues or seasonal demands, or even an ace public relations team to counteract the voices of the competition.

If you cannot tell which way your project is pointing, getting to your destination can be problematic at best. If you also cannot adjust the direction in which your project is heading (project direction control authority cannot overcome or counteract the disturbance forces), missing your target is guaranteed.

6. Implementation on the CxP Space suit Project

The initial mission of the CxP was to provide U.S. access to the International Space Station and then develop the transportation infrastructure and capability to perform sortie missions to the moon in preparation for human missions to Mars. In formulating the CxP design reference missions and architectures for different hardware elements, the development of the space suit architecture evolved into a suit that was modular and could be reconfigured during the mission to meet the needs of current mission objectives. The goal was to reduce launch mass by limiting the number of suits each astronaut had to take – given that historically a crew member would have a specific suit for a particular environment. The space shuttle crew provides a good example of launching two suits per crew for those who are launching in the orange advanced crew escape suits (ACES) and then a subset of the crew who will perform extra-vehicular activities (EVAs) will also launch with the big, white EVA suits (ISS EMUs). The new approach taken by the NASA CxP Suit Element Team was something that had not been undertaken before and, therefore, required a new way of approaching the problem and a new way of doing business.

From the onset of the project and the formulation of the CxP Suit Element acquisition strategy, it was planned that to save schedule time a NASA team would develop the suit architecture, expand associated requirements, and perform the preliminary design in parallel with the prime contractor (which would finish designing the suit and building the flight hardware) selection and putting contracts into place. With this approach, it was evident that the project team, the way the team was managed, and the associated tools would need to be dynamic and flexible. To that end the author's experience with modern adaptive GN&C and experience with large NASA programs and how they could be integrated came into play in leading the CxP Suit Element engineering team such that, during the five years the team never overran its budget and was only responsible for a two week schedule slip during the project's second year. All the while, the team implemented all of its mandated NASA and CxP project control requirements: implementation of EVM, WBSs, resource-loaded schedules, a textbook systems engineering approach, and program reporting. The team also led many other NASA teams in setting up and using mandated document control systems as well as developing project control processes and structures.

The team, in the earliest days of the CxP space suit project, was required – due to an already aggressive CxP schedule – to develop a first revision of functional design requirements within four months not only to support program-approved System Requirements Review milestones, but also to have the requirements available for the release of prime contract request for proposal. For the team to succeed it was imperative that it operate as a high-performance team and be managed as such. And, like high-performance aircraft, so, too, the principles applied in its management.

In high-performance aircraft, the typical mission profile is dynamic and fast paced, so it is imperative the pilot know exactly the aircraft's position, velocity, and attitude in real time, otherwise the mission objectives or the life of the pilot may be in jeopardy. This, in turn, defines the type, quality, and speed and accuracy with which the aircraft's avionics collect and provide this information. While it was fairly certain that none of our team members were in such dire danger – besides the occasional tongue lashing – the need for real-time status of the team and an accurate assessment of progress status was critical. The team operated on a well-defined weekly process [18] for developing, reviewing, analyzing, editing, and approving element and subsystem space suit requirements. Status was provided to the project manager (the author) at an early morning tag-up in which any issues or roadblocks were discussed, and through the day as the project manager walked around to the different subsystem teams and then at the close-out tag-up at the end of the day on Fridays.

An unreported problem that might result in a schedule slip of just a day or so was an unacceptable outcome, given the extremely success-oriented schedule under which the subsystem teams operated. As with high-performance aircraft, the subsystems had to work well independently, communicate with other subsystems, and communicate on prescribed schedules to the project manager who, in turn, had to assess the information and provide a guidance update to the team and produce the desired product to the agreed-to schedule. Information had to flow frequently and accurately across the subsystems, up the management chain and down to the working troops with the metrics needed being meaningful to the tasks at hand being managed. This is where the *system-of-systems* approach came into play with guiding and managing subsystem teams that operate independently as possible while exchanging information frequently with sister subsystems and working in concert with one another.

Some might say, "How is this any different than any other high-performing, rapid response team?" To that the answer is given: In this situation, the team was formulated; and the process by which it would operate, communicate, and share information as well as its latency and applicably to what was being controlled were modeled and documented in the very same way a vehicle's GN&C system would have been designed – even down to understanding the mass, spring constant, and friction coefficient quantities of the team. And, the subsequent damping response of the team was used to modify the processes and limit the size of the team based on the unique team dynamics. At the end of four months, the team had met the schedule deadline and delivered the first 500-page version of the CxP Suit Element requirements document [19]. While there was a requested subsequent two week stand down to perform an internal review to ensure the team did not move too fast to deliver a quality product, it was found that no changes were necessary. During the four years subsequent to this activity, the requirements document was only revised three times as it was required.

Once the initial requirements generation phase of the project was complete, the team moved into a requirements validation testing, analysis, and preliminary design phase that was less demanding in terms of schedule but challenging none the less. At this point, the team structure, the way in which it was controlled, its project metrics, and how guidance was applied to it were revamped to meet the new operational environment and expectations.

Since the Suit Element was required to report budget and schedule actuals monthly, an internal monthly review prior to the formal review but, due to the pace of the project team status, conducted with less latency was required for internal management. Therefore, early Monday mornings the project manager would meet with subsystem leads to get the weekly status and perform short-term planning as necessary. At these weekly tag-ups, on a rotating basis, each subsystem would have its schedule and corresponding status reviewed with the project manager and other subsystem leads. On Tuesday mornings the entire team, spanning multiple support contracting companies and two NASA centers, would have a one-hour integrated-team status meeting that would then be followed by a meeting of the Suit Element Control Board at which baseline architecture, requirements, project scope, and schedule planning packages were controlled. The structure added by the control board provided the majority of the system dynamic response for the team and the Monday morning tag-ups with the leads acted as the system caution-and-warning system. The new dynamic response (spring-mass-damper behavior) of the team was also updated and reflected in the project schedules and planning packages. Successful implementation of this is evident in the afore-stated budget and schedule performance history of the suit project.

Control of the team and its associated tools, processes and information was set up in accordance with not only what was mandated by NASA but also under the GN&C control principle that a control system's model of systems dynamics must represent how the input corresponds to the desired output and subsequent system performance. Beginning with the required implementation of EVM, the team created the WBS dictionary for different development phases of the project. The resource-loaded schedule was then structured to map to the WBS, as were the funding, charge codes, and risks. Project managers have effectively three large levers to pull on to control a project: scope, schedule, and funding. So, the system put into place would have the scope, via the schedule, respond to a change in funding. Similarly, the effects of either of the other two were affected by a change in the third[10]. While this is not a new concept, it was set up so there was a direct correlation that was more quantitative than intuitive that, at a high level, can be equated to control of a vehicle's position and velocity mission activities.

[10] It should be noted that the risk mitigation plans were tied to the appropriate WBS which were linked to the budget planning and schedule; effectively linking the risk mitigation plans to the base-line budget and schedule.

Lower-level processes and statuses were also performed based at the planning package level, but on work actually under way; these were implemented and internally referred to as Requirement Analysis Cycles (RACs) and Design Analysis Cycles (DACs). At this level, they were managed in terms of *progress management* rather than managing to a detailed Gantt-chart schedule. This lower-level progress management, to employ a vehicle analogy again, was used to ensure and measure the health of the subsystem and the quality of the products or output – similar to a vehicle Integrated Vehicle Health Monitoring (IVHM) system. And, even at this level the latency, the subsequent observed system response per equations discussed before, was used to adjust and develop new reporting frequency and tools. One such tool, the DAC Tracker™[11], was developed using Google Docs. DAC Tracker™ is located in the Google computing cloud, allowing multiple people to update simultaneously, and the document can be exported into the format used by the team's software for reporting. So now the subsystem status gathering latency went from greater than a week to a matter of hours. This report was reviewed each Monday with the leads and project manager for all subsystems so that lowest-level issues could be addressed on a weekly cycle and any needed subsystem-to-subsystem integration could take place.

The DAC Tracker™ is an example of how the team's responsiveness to input, λ, was observed and indicated an under-damped system – system took longer than expected to reach a desired goal/state and the team dynamics were adjusted to gain performance. Previously the RAC/DAC status were gathered once per month per subsystem. If an issue was identified in a subsystem review it might be over a month before the next status update was provided and some measure of effectiveness reported. By implementing the new reporting process and frequency, it increased the number of opportunities to gather information regarding the effectiveness of a system guidance correction (control input) from 11 opportunities to roughly 50 in any given subsequent 12 months.

Detailed workings of the change, document control, and risk mitigation processes will not be addressed here; however, the same general philosophy was used to understand their purpose and how they affected dynamics and responsiveness of the team, thereby allowing individual needs tailoring.

7. CONCLUSIONS

It has become more and more evident, in the many areas of science and biology in which the study and understanding of natural systems and processes and how the human body works – e.g., what makes us human vs. mammalian – that more insight into the fuzzy line between where physics and biology drive our decisions and actions is vital. Similarly, in the studies into how to control vehicles and systems and the study of artificial intelligence, we are learning more and more about how we as humans behave, the acquisition and processing of information, and the processes required for formulation of thoughts and decision making.

The results of recognizing the applicability of a GN&C system-of-systems management approach to the CxP space suit project and implementation were seen over the 5 years of the project: a team contribution to schedule slip of only two weeks[12], annual budgetary under spend of 5% or greater, an order of magnitude decrease in review item discrepancies at space suit team's system requirements review[13], all the while performing approximately 130 component and suit-assembly hardware tests, four revisions to the configuration managed Suit ERD, and the completion of approximately 180 peer-reviewed design white papers and engineering memos. The key items to understand and help frame the significance of the metrics above are the very dynamic nature of the CxP scope, aggressive schedule, funding challenges and that the suit team was formulated more than two years after the Orion vehicle, of which the suit hardware had to integrate with and be certified for flight for launch that same as Orion. This effectively placed the suit project two years behind from the very beginning, presented project-to-project integration challenges – all within a very dynamic project scope environment. But by utilizing the principals defined in this paper, the suit team was able to adjust to the changing environments and target end states, and was postured[14] for a suit preliminary design review PDR to meet the needs of the Orion project and the CxP.

In reviewing the material presented in this paper, a clear mapping of traditional system-of-systems, which are comprised of machines and vehicles, is similar in complexity and behavior to many of the large and complex project and teams of today. We also now recognize that many of the engineering principles and mathematics behind the GN&C systems can be used to understand how the programs and projects of today can respond, and how they can be better managed by knowledge of their mathematical modeling at the conceptual and intuitive level. We are standing on the edge of a new future of how projects are characterized and managed in the 21st century – much in the same way that the theory and mathematics behind GN&C in physical systems blossomed in the early 20th century, evolving from a

[11] SmithOps (www.smithops.com) was contracted to provide the schedule management and reporting for the Suit Element.

[12] The CxP space suit experienced many schedule slips to milestones, but these were due to re-alignment of project schedule within the CxP and in response to funding changes outside the control or responsibility of the space suit team.

[13] The results of this approach was an order of magnitude reduction of review comments/Review Item Discrepancy (RIDs) against the Suit engineering requirements document (ERD) compared to the number of RIDs against the parent system requirements document. For the Suit ERD SRR, 0.38 RIDs were received per Suit system requirement. In comparison, the parent document had a 2.94 RID to requirement ratio at the EVA system SRR six months prior.

[14] The presidential prioritization of NASA's activities in February of 2010 significantly changed the scope of the CxP program and all projects within; necessitating a review of architectures and a delay in the suit PDR.

practice of empirical design and test engineering to one of highly reliable mathematical modeling and design of highly complicated vehicles and systems.

It is the proposed future that we can take the art of Project Management, as described once by a project manager as "… herding cats in the rain, blindfolded, all the while trying to keep the dogs which are tied to your waist from eating the cats!", to an environment in which the project manger will know when the rain is coming, see over the horizon, know statistically how the cats are likely to behave, and command the dogs such that the dogs are autonomously controlling the herd in much the same way as a well-trained border collie expertly delivers its herd with minimal-to-no input from a shepherd. By characterizing project dynamics in terms of mathematics, it is thus possible to factor out the uncertainties in internal response and behavior of a project and limit uncertainties to the unknown nature of the external inputs, and how the project will respond and adapt to these inputs. Increasing the predictability of project performance and response will reduce project uncertainty in cost associated with schedule and can also lend itself to the tuning of project processes that will be further realized in performance and cost savings.

On a final note, while the scientific, mathematical, and engineering techniques discussed in this paper are valuable, an exceptional project manager will add the strong leadership skills: intuition, courage and commitment to the project.

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BIOGRAPHY

Terry R. Hill *is a member of the NASA Lyndon B. Johnson Space Center (JSC) International Space Station/Shuttle Extravehicular Mobility Unit (EMU) Team where he is responsible for providing engineering insight into the 2010 life extension hardware modifications, determining what the system hardware impacts are to extending the ISS EMU support out until 2028, and investigating how the EMU can be used as a demonstration platform for technology development.*

Terry has a B.S. in Aerospace Engineering and an M.S. in Guidance, Navigation, and Control Theory with a minor in Orbital Mechanics from the University of Texas at Austin. He began his career at NASA while working on his graduate thesis project in developing banks of simplified Kalman filters integrated into an artificial neural network to obtain an optimal state solution for precision landing on Mars.

While at NASA, Terry has worked on projects and programs spanning from ISS navigation software verification to Shuttle navigation design test objectives and back-room mission support, X-38 Crew Return Vehicle navigation algorithm development, Space Launch Initiative technology development, Orbital Space Plane Project office ISS-prime integration, Space Shuttle "Return to Flight" STS-107 tile repair capability development, and to CxP Space Suit Element leadership.

Terry and the Suit Element have been interviewed by the Associated Press and covered by media outlets including CNN.com, Forbes.com, and National Geographic video "Living on the Moon" air date 2009. Terry has also been identified as one of NASA's Constellation Stars, and was identified as NASA Tech Brief's "Who's Who at NASA" for November 2010.

In leading the CxP Suit Element engineering team, Terry had the responsibilities of JSC's Engineering Project Manager, the CxP EVA Systems Suit Element Deputy Lead, and Element Lead during his tenure on the project. He facilitated the development of system functional requirements for space suit development and a "clean-sheet" design approach that has been widely recognized within and outside NASA.