Predictably Effective
Planetary Defense Against Asteroids

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Concepts for a system to provide planetary defense against asteroids are being discussed worldwide. It is fair to say this complex system is in very early design stages[1]. By applying the Complex System Sustainment Management Model (CSSMM) to this design problem, insights on system design can be explored. This paper does that and explains why a Planetary Defense System should be designed in such a way that it can be continually demonstrated to be effective, reliable, available, survivable, economical, anti-fragile, and safe & sure. This leads to a design where the majority of the system is predictable state-of-the-practice hardware and software; the system is made up of many copies of subsystems so that aggregate analysis can be used; and the system is maintained in a state of constant and continuous upgrades. This paper is based on the author's 30 Jun 2018 presentation to the LA-LV Mini-Conference on Planetary Defense Against Asteroids.

I. Introduction

Based on his career sustaining aerospace systems, primarily ICBMs, the author has written 8 previous AIAA papers on the Complex System Sustainment Management Model (CSSMM), provided a dozen presentations, almost 100 blog posts, and taught a 2-hour sustainment tutorial at the 2019 INCOSE Western States Regional Conference[2]. These products are available at his web site and can be read as an introduction to this paper. Alternatively, in the next section, a short description of the CSSMM is provided for the reader's convenience.

Because of this background, the author was invited to speak at the LA-LV mini-conference on Planetary Defense on 30 June 2018. This paper is based on that presentation.

The CSSMM is meant to describe the best system management approaches to be used in the "steady-state[3]" sustainment phase of a complex system. The CSSMM was built upon the concepts, ideas, practices, and successes of sustaining ICBMs for 6 decades. By taking this "sustainment phase" perspective and looking at the very early design phase of planetary defense concepts, insights can be arrived at that not only build key readiness factors into the design of the eventual planetary defense system, but also set the stage for the ability of the eventual sustainers to better observe the system and fix issues more effectively and affordably.

This paper provides a short introduction to the CSSMM, explains what readiness factors would be important in planetary defense mission, and what these factors imply for the design.

II. The CSSMM, a Short Summary

Great philosophical insights have been attributed to Yogi Berra. One of them is:

"It's tough to make predictions, especially about the future."

Yet this is exactly what must be achieved for any complex system being sustained and certainly for a system that is expected to defend Earth against asteroids. If we can imagine a day where the Earth has a planetary defense system, we can imagine that it must be fairly complex to deal with the varied threats. It must also continue to work reliably on day 2, year 2, even century 2 of its existence. To stay ahead of the issues that might doom such an important system to the trash heap, one must predict that system's future problems in order to prepare for them.

This leads directly to the usefulness of considering the CSSMM this early in the design phase. Consider the fundamental theorem of sustainment. (A "fundamental theorem" is a statement that is necessary to create the associated domain of knowledge.) The fundamental theorem of sustainment is:

"An effective sustainment organization will always find ways to affordably detect threats to the system in time to correct them before the mission is impacted."

To achieve this "in time" response, risks must be identified. This can only happen if the system is observed. This can only happen if the system is bounded and defined. The system is more easily observed and evaluated for risks if readiness factors are used in that process. Identification of risks is only useful if this results in risk mitigation ideas that lead to funded long-range plans. All of this is aided by disciplined processes, adequate IT, and dedicated people.

That, in a nutshell, is the CSSMM. The following provides a little more detail.

See Figure 1: The Complex System Sustainment Management Model (CSSMM). The model begins with the need for an effective sustainment organization to predict the future of the system they are sustaining. That is, changes to the system required to keep the system useful must be conceived, approved, funded, and completed in time for the system to remain viable. This impossible task of predicting the future is tackled by creating and executing a formal assessment program to observe the precisely defined system.

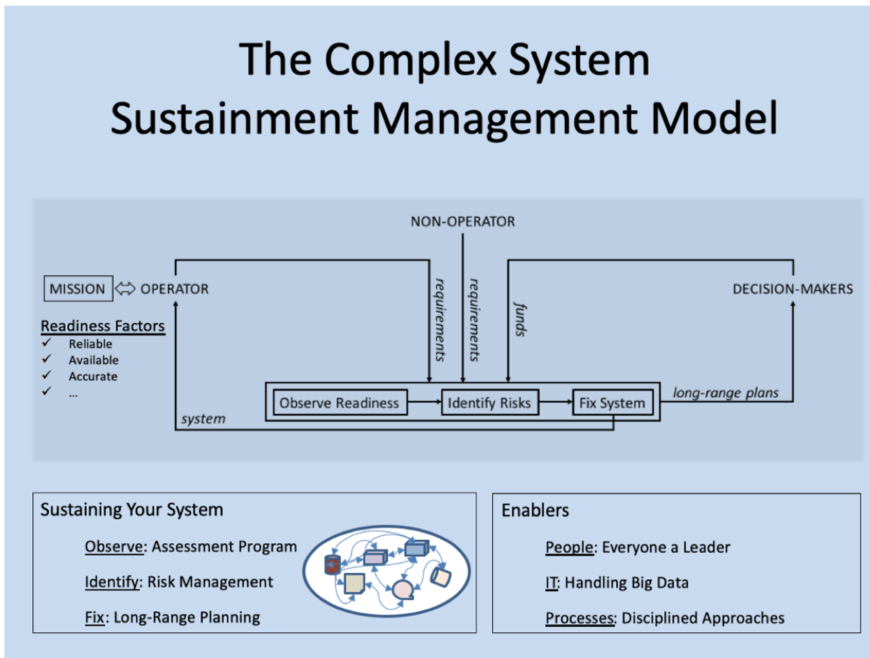

Figure 1: The Complex System Sustainment Management Model (CSSMM)

The formal assessment program focuses on the readiness factors and searches for emerging failure modes. The assessment program begins with the failure modes effects and analysis and similar information handed down from the design team and then they also search diligently for the unexpected emerging failure modes. (Even the best minds in design cannot think of everything for all time.) Once found, the team characterizes the physical properties of the degradations. It is usually safe to assume these physical properties being modeled and analyzed continue along some logical, physical path. For instance, on-board batteries generally degrade in predicable ways[4]. Therefore, the mathematical models can be extended into the future with some certainty[5].

A good assessment program controls for errors. They look out for a bad design of a predictive model. They consider whether the environmental conditions have changed in some way over time in deployed systems or in tests. Have there been any unforeseen interactions of chemical processes? Has data stored in data bases been compromised? It there an unexpected additional emerging failure mode that interact with the first one? And more. Experience helps a lot here.

If the system has many copies within its subsystems, assessment experts use the ability to aggregate data on all the copies to characterize the likelihood of mission success overall. They use operational data if available and they also design tests to acquire the needed data.

For instance, in ICBMs, age surveillance is used to track known expected age out or wear modes over time. Aircraft use a similar system to track the aircraft with the most flight hours, often purposely tagging one or more aircraft for this method and flying them much more than the others.

The execution program (the part of the sustainment activity that makes the mods and fixes to the systems) drives understanding and further requirements back into the assessment and risk management programs. For instance, in a military example, program element monitors must be able to take risks and long-range plans and succinctly explain them to boards of general officer decision-makers in order to be successful at obtaining funds for system mods. When these mods are made, the assessment program tracks their success or failure.

Enablers that are needed to make this approach work are classified under "people", "processes", and "IT". The massive amounts of data required to perform observations and make sense of them to the point of creating long-term plans require strict process discipline and a continuing investment in IT-type resources: data storage, analysis tools, and associated skills that are nimble enough to keep improving these activities. The most important element among the individuals and teams working in these areas is *speaking up*. Processes create continuing opportunities to identify risks, but only individuals can make the choice to speak up about them. Individuals who do not speak up or who demonstrate incompetency in their field cannot remain on their team.

To take it full circle, the most powerful tool available to motivate individuals to contribute is dedication to the mission. In the case of ICBMs, the mission was global nuclear war deterrence.

The mission of a Planetary Defense System should be to protect the Earth against asteroids that could penetrate the atmosphere and cause significant damage on the ground. For the purposes of design, this is usually taken to mean damage that could destroy several blocks of a city or worse. The mission should also include the concepts of the survival of the human species in a clean and diverse environment that doesn't destroy the global economy and can be sustained over centuries. This paper will use this definition of the mission of the system. A better one will arrive with time and be improved over the period of time that the system is sustained.

What would the system itself look like?

Broadly speaking, a Planetary Defense System would need (among other things) world-wide and orbital sensors (both Earth and Solar) to find and track asteroids, a command and control capability to trigger the defense, and then some kind of active weapon designed to eliminate or reduce the destructiveness of the asteroid. It is likely that, at least in the near term, many copies of rockets would be part of the third major subsystem. In that sense, much is very similar to ICBMs. In many instances, nuclear warheads might be the best way to reduce or eliminate the effects of certain asteroids, but in most cases, this would not be needed[6].

This description should be reminiscent not only of ICBMs but also of defense against ICBMs. In fact, the detailed requirements would be very similar to the Ground-Based Mid-Course Defense system currently in place at Fort Greeley, Alaska and Vandenberg Air Force Base, California. This system is in a constant state of improvement and modification.

III. Readiness Factors

In ICBMs, the readiness factors are availability, reliability, accuracy, and hardness against nuclear attack. Many sustainers add safe & sure. However, the system would not be allowed to exist, and thus not be available, if it was an unsafe nuclear weapon which folks might be unsure about when it might explode. In ICBMs, each of these readiness factors have precise definitions and associated target numbers which, when met, mean the system is meeting its mission.

Given this mission and description from the section above, the following are the readiness factors proposed by the author for this complex system. These readiness factors met with general approval when briefed in June 2018 to the LA-LA mini-conference on Planetary Defense.

Effective

A planetary defense system must, first of all, defend the planet. It eliminates or mitigates threat. This, of course, is a fundamental design criterion. Precise definitions must be created to explain what success in this arena means.

Some general ideas would be 100% success in saving the humanity. 85% success in saving specific cities or regions. These numbers are tweaked depending on what technology is available and how much funding can be expected.

Reliable

The system must be reliable. In other words, all required functions work. This readiness factor would probably be defined very similar to ICBMs where reliability is measured as delivering the warhead with, let's say 75% reliability (this is NOT the number used by the ICBM folks!), given a valid launch command has made its way to the launch facility. Perhaps this reliability factor will be assessed based on salvos of rockets being launched against a single target in order to up the probabilities of success. There will also be reliability numbers for the ground systems and space sensors. Reliability can be allocated down to the subsystem and components, and those pieces and parts can be subjected to periodic tests to ensure their reliability is not degrading.

Available

As the system is used, it must be always ready to be used when needed. This requirement remains even immediately after it has been used. This is similar to the GMD where a field of rockets stand ready to launch even if a few have already been launched. Just like reliability, numbers can be created to track the lower indenture level parts and subsystems to track their on-going availability.

Survivable

The world can be a dangerous place and complex systems can be attacked and damaged by both nature and mankind. The system must survive these attacks and be ready to work within a moment's notice.

Economical

A system that is not affordable will eventually be discarded. It must be kept viable with resources available.

Anti-Fragile

There is increasing evidence that even highly complex systems can be designed to improve with stress. This leads to a design which is expected to be not only maintained but upgraded as circumstances dictate. New design ideas are emerging every year in this area, especially in software and artificial intelligence.

Safe & Sure

The system cannot harm people, things, environments. The system works only when commanded. This is similar to nuclear weapons in that a system that does not provide this assurance will not be allowed to exist. This is especially important if the system does include some nuclear bombs.

IV. Design Considerations

Because significant resources would be required to create and maintain the system discussed above, a planetary defense system must be continually demonstrated to meet its mission – especially to those footing the bill. That is, it must be predictably effective to ensure that it will be supported, maintained, and (especially important) improved over the decades.

These guarantees can come in the form of monitoring, testing, and analysis; risk identification; and an on-going collection of risk mitigations integrated into an executable long-rang plan. These are all characteristics of the CSSMM.

In ICBMs, operational data is collected and saved in massive data bases which also includes analysis tools. There are tools for cross-talk between data bases. For instance, one data base can provide the latest information on gyroscope health in the guidance system based on current calibrations and another system can provide gyro characterization factors for that serialized gyro and the two data bases can be easily accessed together to form a degradation opinion. Using operational data reduces the need for testing guidance systems and gyros to track their reliability. In general, collected available operational and maintenance data is a cheaper approach than any other. But it does not provide sufficient data across the entire system and across the entire spectrum of readiness factors.

Age surveillance testing is planned and executed for specific degradations that are expected over time. In addition, these results are scanned for unexpected, emerging failure modes. These inspections and tests must be consistent over decades to make the results meaningful.

Even more additional test must be planned and executed to round out the full observation suite.

These concepts lead to design requirements where the majority of the hardware is predictable, state-of-the-practice; many copies of systems and subsystems exist to support aggregate analysis; and the system is in a state of constant and continuous upgrades to deal with new requirements and risk mitigation mods. This is somewhat similar to the current ICBM force but very similar to the current GMD.

What might this look like for a planetary defense system? Imagine a test program similar to the ICBM test program where 3 to 4 rockets are launched each year. These launches can be exploited to try out new concepts and systems in planetary defense. Perhaps two rockets intercept an asteroid to attach rockets. Then the rockets are controlled from Earth. The other two might deploy a kill vehicle whose effectiveness to maneuver and initiate is tested. The following year, another concept might be tested such as directed high energy weapons to vaporize a part of the asteroid to create a diverting force. Operational and developmental tests will be a routine part of this system. It would be a system designed to evolve as requirements are better understood and technology provides new answers.

V. Conclusions

It is certainly not possible in 2500 words, or even 25,000 words, to take the combined knowledge of ICBM and missile defense sustainment and give even a short summary of a design specification for planetary defense. However, this paper has demonstrated that comparing the CSSMM to the planetary defense mission can result in useful insights that should appear in any future planetary defense specification.

Constant re-visiting of what the mission and the system are, how sustainment of this system would work, and externals like decision-making and funding organizations mean that this exercise should and can be repeated to great benefit as the planetary defense system requirements are created, realized, and sustained.

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[1] If planetary defense is all new to you, a starting point into this domain is planetary.org. Or see my blog post: charlesvono.com/planetary-defense-and-sustainment/

[2] See charlesvono.com and follow the first menu item to "Presentations and Publications" to download full papers and presentations. Or go to AIAA's ARC and enter author: Vono. Start with Vono, Charles, "Fundamentals of Weapon System Sustainment", AIAA SciTech 2016, January 2016

[3] Steady-state is placed in quotes because experts know that the systems they sustain are never at rest but require constant modifications to remain effective in their missions. For a discussion of differences in the design phase versus the employed phase see my blog post: charlesvono.com/a-good-question/

[4] In Minuteman III ICBMs, a famous degradation mode was found in a battery that was totally unexpected and discovered only because a technician noticed a funny yellow powder on a few of them after some routine tests and told an engineer.

[5] As a minimum, this task must include both a statistician and an engineer to help ensure both the model and the basic chemistry or physics of failure are really understood.

[6] For a pro and con discussion of the use of nuclear bombs in planetary defense see:
anti-nuke argument: aerospaceamerica.aiaa.org/departments/nuclear-nonsolution/
pro-nuke argument: aerospaceamerica.aiaa.org/departments/earths-best-defense/
What might be done without nuclear bombs? Kinetic impact. Directed energy. Placing devices on the asteroid to nudge it using various schemes. These and other options are already being debated. Key to this debate is effectively categorizing asteroids into groups. For instance, broadly speaking, a lot of time and distance allows for lower energy "nudging" solutions. But lack of warning time severely limits options. Many other categories are being discussed as well such as what the asteroid is made up of or how many pieces and what shapes the asteroid is.