Recapturing System Decomposition Techniques for Improved S&T Development of Future Warfighter Capabilities

Abstract

This paper explores the rediscovery of system decomposition techniques such as Work Breakdown Structure (WBS) as useful systems engineering tools for planning, executing, and transitioning Science and Technology (S&T) programs. Many well established techniques are routinely used in costing and scheduling work, as well as to identify critical technology elements in technology-readiness assessments. However, they are rarely used to generate candidate technology alternatives in early S&T planning, which generally lacks the imposed structure dictated by the existence of formal requirements. Decomposing an S&T development into its functional, physical, or work components makes the problem more manageable. The program manager is inclined to make simplifying assumptions to scope the program into something more familiar and limited but, in the end, not transitionable. The danger is that the system aspects that are assumed away and solutions that would result from their consideration are lost until further development, when they emerge and stand in the way of satisfying a Capability Concept. It is important to recognize how the S&T may fit into end uses or systems. Otherwise, as is too often the case, technology that is desperately needed faces serious delays—sometimes even years—while the interfaces are developed and implemented. This paper demonstrates how existing techniques can be tailored to applied research and advanced technology development efforts that are ultimately aimed at Capability Concepts. Novel application of these techniques satisfies the need to decompose the problem into tractable elements while maintaining awareness of the complexities and interrelationships within the system. This paper illustrates the value of these techniques by means of a case study that highlights the generation of candidate technology alternatives to fully explore the feasible solution space before zeroing in on the recommended solution and its integration challenges.

Background

S&T, Science and Technology, does not lend itself to the more evolved processes and common tools of Systems Engineering (SE) that apply to mature technology. The concepts are identical, but at the S&T stage there are inherently severe knowledge gaps. Explicitly identifying and addressing those gaps can be the difference between leading, following, or even being irrelevant.

What is a "system?" The pertinent answer for these purposes is "whatever those responsible for it decide it is." It makes a difference—sometimes the difference between success and catastrophic failure.

"How long does it take to transition a technical concept into production?" Obviously that depends upon the technology.

Probably not.

The technology has an impact, but the organization makes the difference. The best organizations consistently transition technology from concepts to application in 10–20 percent of the time of their less driven competitors. Time is money; so that shortened timeframe also translates into cost savings, often of the same magnitude and always substantial.

The numbers can be dramatic. At one point not so long ago, it was revealing to watch two industrial competitors, one in the Pacific Rim and the other a US Fortune 100 company, working toward the same ends in the United States. The Fortune 100 company spent $3 billion and 6 years to do a job the Pacific Rim company accomplished for $525 million in 14 months. The Pacific Rim company, while never actually using the term "systems engineering", took a *system* view of their effort and anticipated issues while the Fortune 100 company chose to react slowly to each unanticipated issue.

In the late 1990s an international high tech firm realized their products were consistently delayed reaching their markets by what they euphemistically called "the sheet metal." The small gears, brackets, hinges, linkages, and covers necessary for their commercial products were "afterthoughts" to their technology-based market strategy. Their effective response was a highly automated "systems" approach with basic design decisions early in the development process. The "sheet metal" was ready to go ahead of their vaunted technology products.

In the mid-1960s the United States adopted the M-16A1 rifle and began experiencing catastrophic failures in combat. The problems were resolved in what amounted to a redefinition of the rifle "system" and corrective action that recognized that both the rifle *and* its ammunition are part of the same system. Though the failure occurred in full-rate production, the rifle and ammunition were developed along parallel paths based on assumptions made at the S&T stage, without integration testing or other system considerations before fielding the weapon system.

A US Fortune 50 industrial equipment manufacturer faced brutal competition around the world. Their S&T efforts were consistently late and underperforming. On a trial basis, they tried subcontracting critical technology development, usually elements rather than systems, to specialty firms. Developments that the manufacturer had struggled with for years were finished in months, sometimes weeks. The far more difficult challenge was the revelation that their product design efforts were based upon obsolete system designs and a radical reallocation of system functions was essential to surviving in their competitive environment.

> "A few years ago we had the problem of getting an effect that required a small kinetic warhead [to detonate] within a few feet [of the target]," he says. "We had the platform, the delivery vehicle and a weapon with enough accuracy. What we did not have was the [communication] pipes to get information because nobody had thought through the end-to-end, system-of-systems acquisition piece."[1]

In all these examples, there were costly delays that could have been avoided by more careful thought in recognizing, defining, decomposing, and analyzing the system early in the S&T cycle.

The objective of this paper is to encourage the S&T community to understand the implications to the development cycle of the context in which its S&T products will be used and of the choices made during S&T development. Sometimes difficult within S&T, the end-use environment is unknown; even in this case, it can even be useful to explicitly recognize this fact.

System Definition and Decomposition in S&T — Essential to Success

Think of a *system* as something that performs one or more functions and is created by integrating independent elements with their own functions. *Systems* occupy a continuum from simple to complex. Though it usually would not be, a mechanical pencil can be described as a system; it consists of a marking element (lead), an extension-retraction mechanism, a holder (housing and grip), and possibly a corrector (eraser). In practice, we think of systems as far more complex than a mechanical pencil. A modern airliner is a system, and sometimes the term *system of systems* is used to capture that higher degree of complexity. An airliner is an integration of obviously sophisticated elements (subsystems) including propulsion, avionics, flight control, and structure, at a minimum. Each of these elements is also complex; so, for example, avionics has its own set of components or subsystems. Again, the important notion is that a system is an integration of independent functional elements.

System creators and analysts use a process called *functional decomposition* to describe and conceptually visualize the various elements that are integrated to form the higher level system. At its purest, functional decomposition breaks out the individual functional elements. The focus on *function* is critical. Function has to be separated from product or solution, particularly in the early stage of establishing objectives (requirements). A cruise ship has a functional requirement for directional control. The traditional solution is a rudder. If the functional requirement is defined in terms of a rudder then neither auxiliary thrusters nor the more capable 360-degree rotating propulsion pods would exist. The most common graphical convention for a functional decomposition is a hierarchical chart format similar to an organization chart.

However, there is a fundamental problem with functional decomposition. Decomposition assumes a composition.

In the S&T realm, systems usually have not been defined; so, by definition, they cannot be decomposed. If decomposition is undertaken, it typically reflects current state of the art. It may even appear to be a misnomer to think of "decomposition" in S&T and historically we have not, or at least the decomposition is implicit rather than explicit. S&T emphasizes advancing specific technology with a narrow set of functional requirements, sometimes only one. Someone, somewhere in the larger organization may have a vision for specific S&T in a larger context, but it is not a priority to explicitly convey that vision to the research team. Often, however, this omission has ramifications because context is significant.

The notion that functional decomposition requires a composition is somewhat academic. At least in theory, in system design, functional decomposition is executed in the synthesis stage. It is an iterative process. At that stage, though still referred to as a functional decomposition, it would be more accurately described simply as a *functional hierarchy*. The other term sometimes used in the synthesis stage is *functional allocation*. Although they are no equivalent, the terms *functional decomposition* and *functional allocation* are sometimes used interchangeably; so the intent must be inferred from the context.

The issue is more than a purely semantic one. Too often, S&T and system design are driven far more by prior state of the art or market than by recognized functional needs or they are driven by fascinating technology with limited application potential. The key issues for S&T are the following:

- S&T is often if not usually based on improving prior art or substituting prior art. A *systems* view may drive the S&T resources in a different direction or may better allocate functional requirements.

  For example, early efforts at building all-electric vehicles envisioned replacing gasoline engines with electric motors while retaining conventional transmissions and placing batteries in the fuel-tank area. Rethinking the functional requirements opened up the possibility of pancake electric motors directly on two or four of the wheel assemblies, eliminating the transmission. Even that view is limiting.

  Improving the quality of video tapes and related equipment may not make sense if the S&T team has created near-random-access, high density, and potentially cheap optical storage devices (CDs).

  Assuming pilots will continue to fly in combat aircraft, with all the personal protection required and risks incurred, may be limiting both the technology possibilities and the types of missions that can be prosecuted.

- S&T *rarely* includes an assessment of the ancillary requirements to enable its practical application. The S&T technology is either *obviously* valuable or in the *discovery* process wherein its value is thought to be unknowable.

  Wind turbine generators may be a terrific idea, but, at least within the US, a practical distribution grid is years, probably decades away.

  Electric cars may be a solution to myriad local, national, and international issues, but charging them remains an obstacle to adoption.

  The M-16 proved to be a significant improvement over prior art, but once every warfighter had an automatic weapon, production of adequate quantities of ammunition was problematic and the initial solution was a deadly catastrophe.

  Much like the broadening demand for Unmanned Aerial Systems (UASs) beyond military applications, more than a year after purchase, the State of Ohio's new $3 million aerial digitizing camera system cannot fly because it fails to meet FAA requirements.

  Environmentally friendly waterless toilet systems cannot be installed because they do not meet codes designed for flushing water systems, and there are labor elements opposed to any changes in those codes and the work that comes from installing piping.

- S&T researchers may inherently lack the experience to envision their work in a larger context and cannot in isolation identify the external barriers to applying their technology.

Let us be clear. The issue is not that S&T is fundamentally flawed. The issue is that there are unrecognized barriers to implementation and the benefits of the S&T. These barriers can and often do seriously delay our ability to exploit S&T.

The Opportunity

A hybrid WBS improves the probability that S&T will actually be implemented in a timely manner delivering value to the end user—in the defense environment, the warfighter.

- It reveals obstacles to implementation of the technology, ancillary technology, and other issues that need to be considered and resolved in parallel with the S&T of interest. Failure to recognize and address these topics can lead to terrific technology that sits on the shelf.
- It helps to reveal a broader range of S&T alternatives that may have a high probability of meeting the end user's needs.
- The questions necessarily asked and answered in the creation of the WBS reveal essential and often unconsidered characteristics (desirements) that the S&T has to satisfy to be accepted.
- The WBS process, and the SMEs necessarily involved, can help to identify potential applications of the S&T that the researchers would never have considered. That knowledge can have critical impact in prioritizing S&T investment.

The WBS can be the first step in assuring the value and timeliness of S&T.

Creating the Hybrid WBS

A functional decomposition, or functional allocation in the organizational chart format, is a powerful and revealing tool for identifying a broader range of S&T alternatives that may satisfy an end user's needs and barriers to success in delivering that S&T. For S&T, it makes sense to be very, very flexible and open-minded in building the chart.

- The organizational chart format is familiar, easily understood, easy to execute without special software, and quite adequate for most S&T circumstances. Other types of diagrams, such as IDEF, entity-relationship diagrams, mind mapping, and those described in the US Department of Defense Architecture Framework (DoDAF) may be more revealing, but they are also labor intensive, are best executed with special software, and may be confusing to those not familiar with them. At the S&T stage, the level of detail implied by the alternate formats may be justified after the simpler hierarchical organization-chart format reveals a need.
- Break the rules. The purist will insist on a chart that has strictly functional elements. At the S&T stage, it is more important to capture the thoughts. Hence, a mixture of functional elements and solutions may be useful. Solutions rather than functions imply underlying assumptions that lead back to the functional requirements. Capturing solutions first can help reveal those drivers.

- Accurate, precise, detailed functional diagrams have deep implications for design and are simply not appropriate in the S&T environment. For example many modern systems have sophisticated controls. Whether the controls are centralized, distributed or hybrid often has deep implications that simply cannot be effectively addressed or known in the early S&T phases.
- Expect to be challenged and to learn from the process. There are always surprises.

Work Breakdown Structure Terminology

The Work Breakdown Structure (WBS) terminology and form probably have their roots in the same term applied in the disciplines of Project Management (PM). WBS has a very precise meaning in MIL-STD-881 and may be incorporated specifically in contracts. When used in the Systems Engineering context, the term *WBS* may have a meaning that differs from traditional meanings, though the graphics may appear similar, and the differences may not be obvious.

Similarly, Systems Engineering uses the term *architecture* to describe the diagram used to illustrate system element interrelationships.

The terms *work breakdown structure*, *architecture*, and *relationship diagrams* are often used interchangeably. There is also a continuing discussion about the differences between Project or Program Management and Systems Engineering.

It is useful to recognize these similarities and differences in meaning and intent. They are definitely important in the system design and execution stage, but early in the S&T process it is more important to capture the thoughts first and clean up the semantic abuses later.

Following common practice, we use the term *WBS* as it has been generally co-opted to mean a hierarchical graphical format to illustrate notional relationships within a system. That is all. Early in the process, mixing solutions and functions helps to capture important considerations that can be properly sorted out in a subsequent process.

The Streamlined Systems Engineering Process (for S&T)

For S&T we recommend and use a streamlined System Engineering process that has evolved specifically to apply to an environment where there are many yet-to-be-known details.
See Figure 1.

Examples

Following are a series of examples that help to illustrate the evolution of the WBS within S&T efforts in both defense and private-sector companies working for defense markets. In each case other than the illustrative *Writing Implement* example, the WBS evolved and led to dramatic change in the S&T.

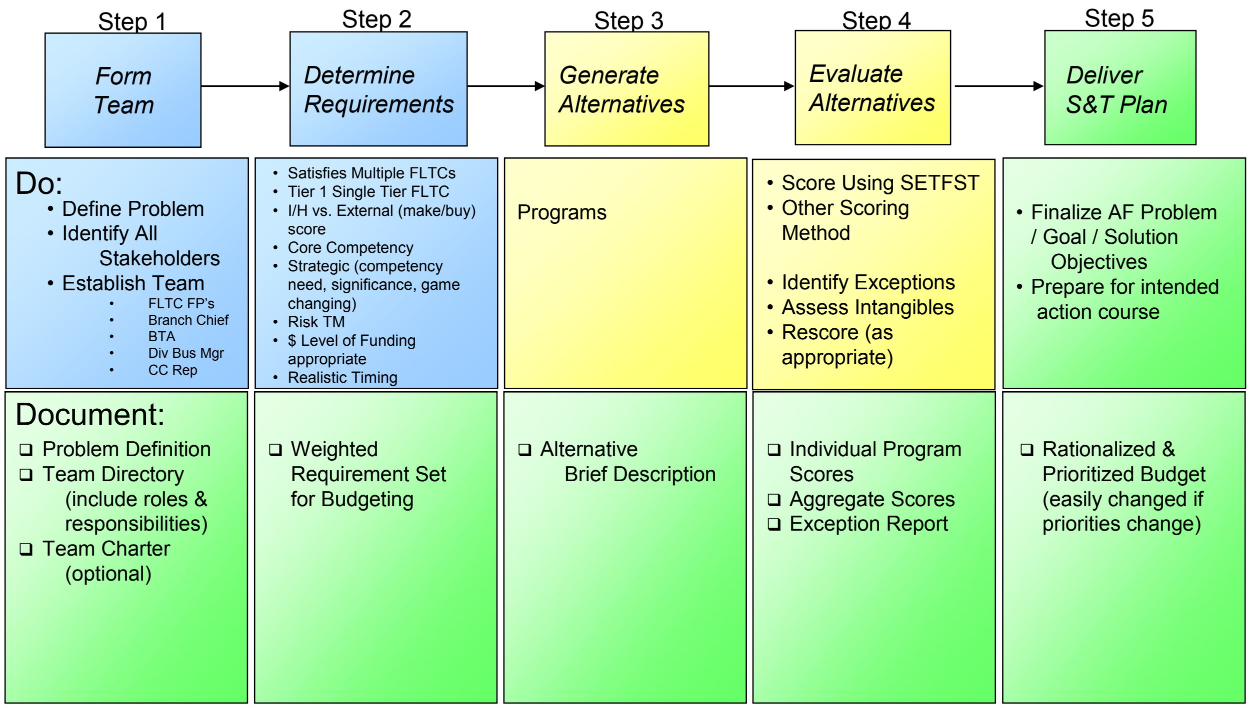

Figure 1. Streamlined SE Process for S&T

Writing Implement

A writing implement is a relatively simple device, deceptively so, because we all have experience with a variety of them. At first pass (Figure 2), we might not consider the writing surface to be part of the "system." When we "test" or "validate" the "system" following good system engineering practice, the writing surface will be part of the test, as certainly will a user (Figure 3). Most of us have experienced the inability to write on particular paper, such as an off-brand sticky-note or glossy paper, or have seen unacceptable ink bleed on regular paper.

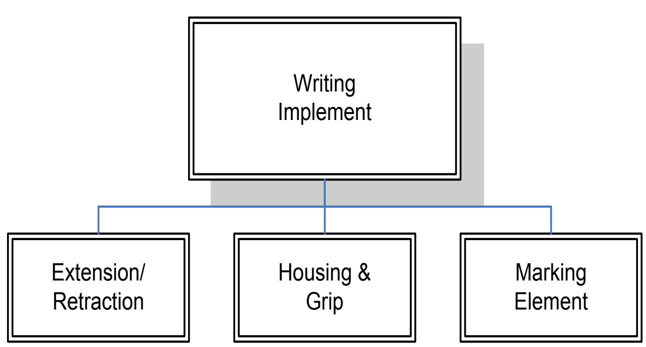

Figure 2. 1st Pass Writing Implement System

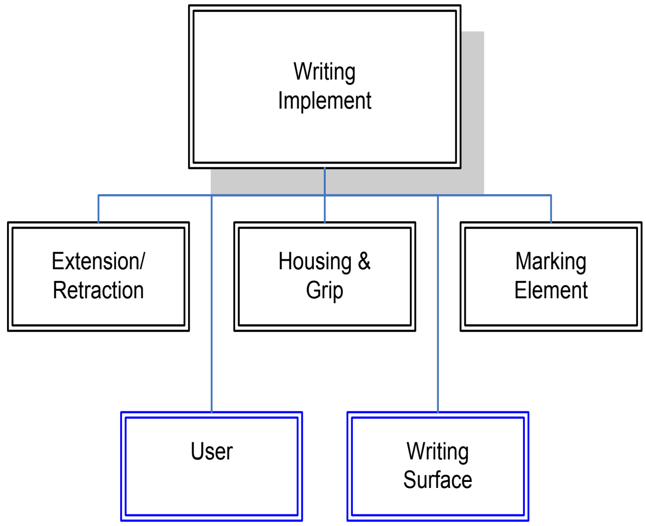

Figure 3. Writing Implement System

Thermal Systems

The traditional thermal control system WBS (Figure 5) deemphasizes the potential for controls in an applied system, hides the potential improvements from heat transfer microscopic surface modifications, and ignores the tools essential for rapid, cost-effective S&T.

Two different updated versions of the thermal management WBS were derived from discussions for S&T work: one an expansion of the traditional WBS the other with more of a physics perspective (Figures 5 and 6). Neither of these is "better" than the other; different perspectives in an effort to identify gaps.

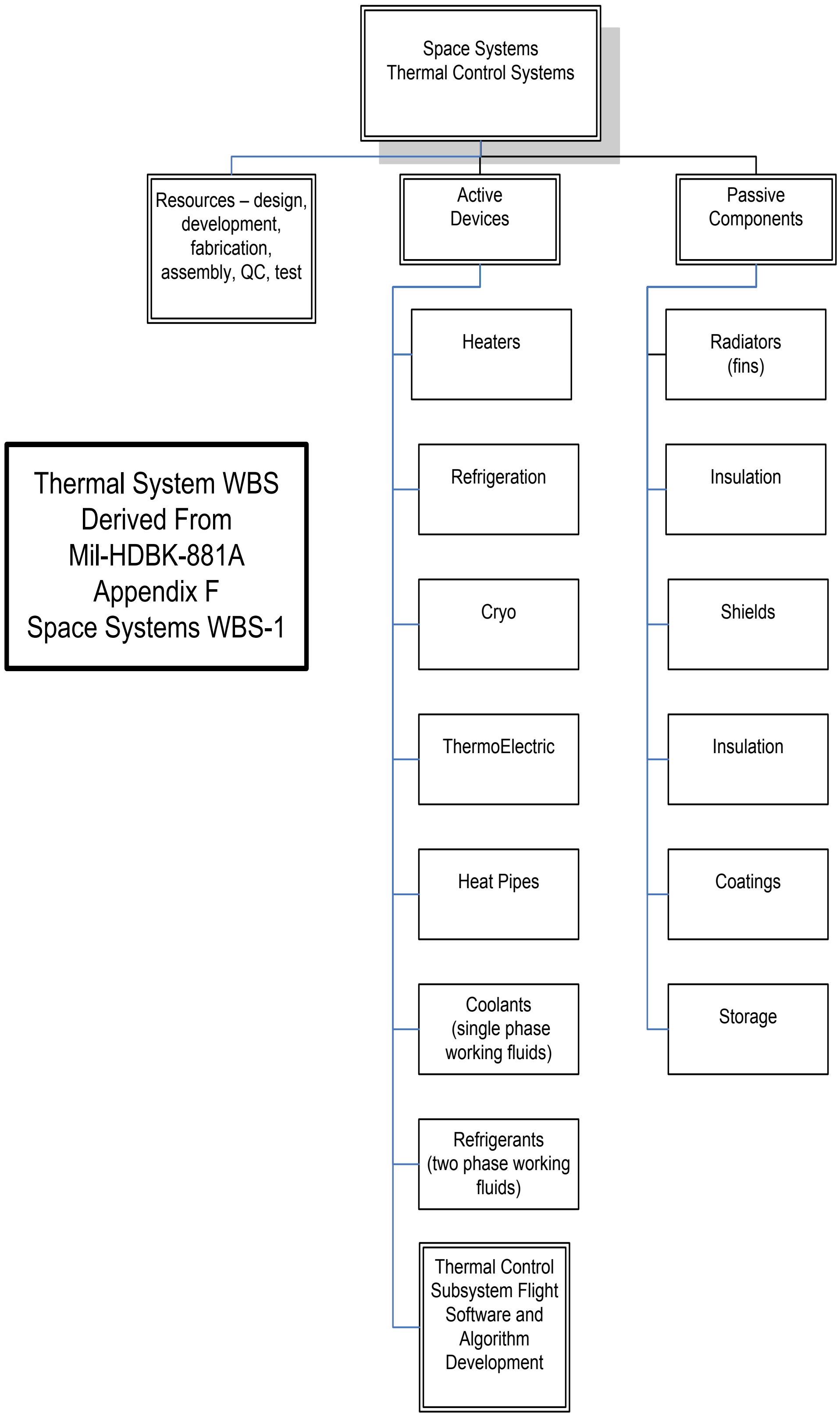

Figure 4. Thermal System WBS Derived from Mil-HDBK-881A, Appendix F, Space Systems WBS-1

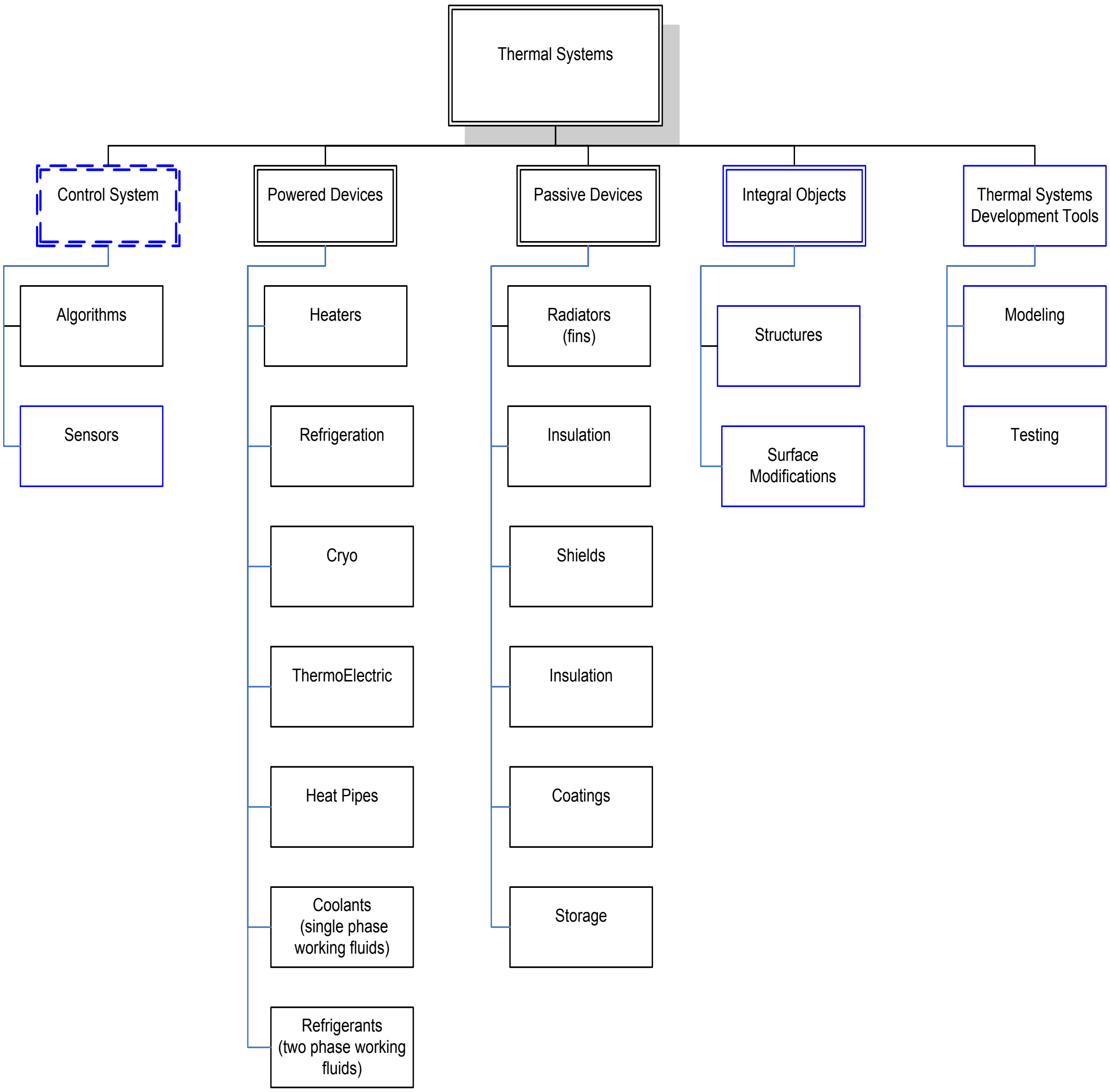

Figure 5. 1st Pass at a More Comprehensive Thermal Systems View

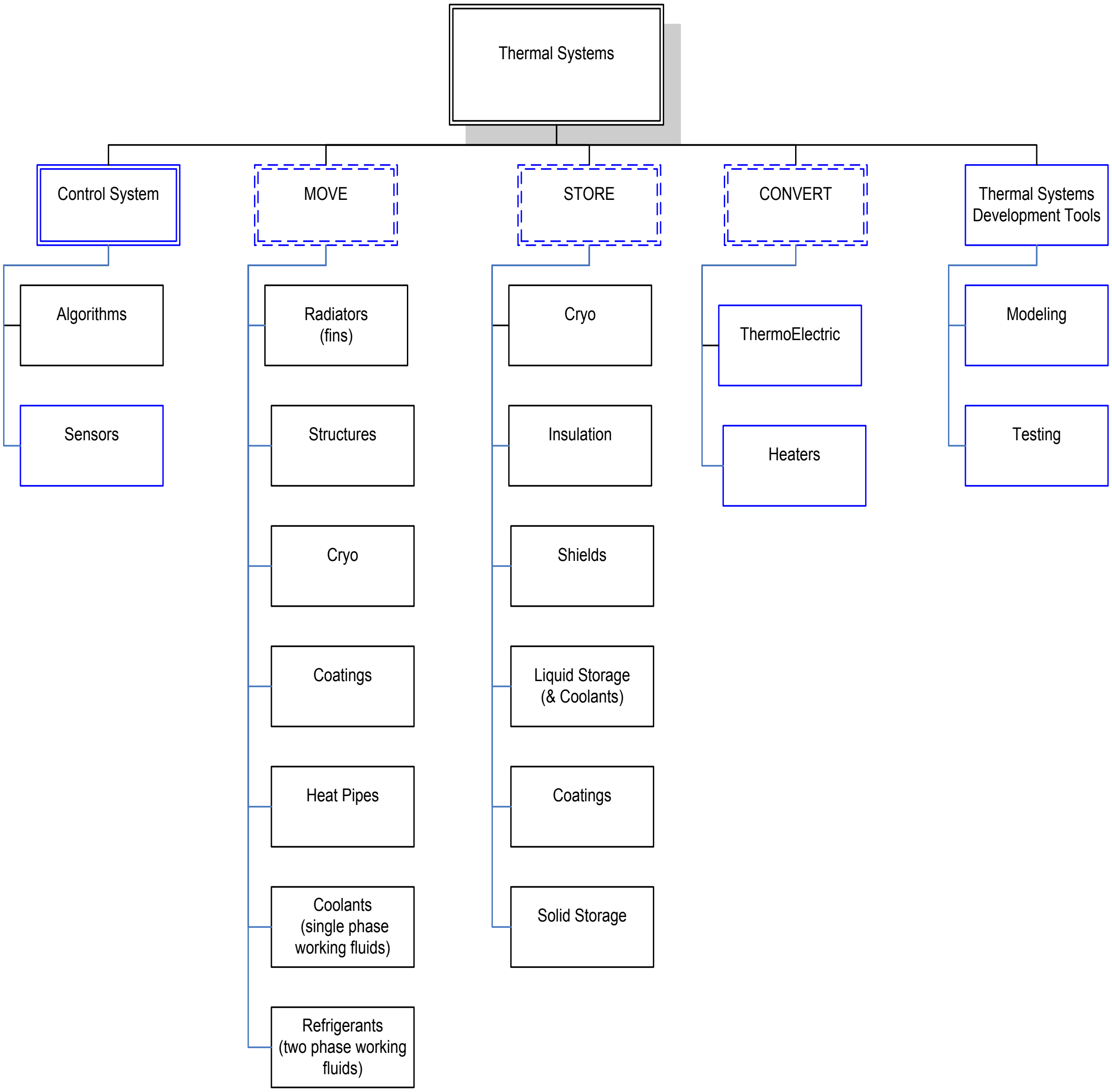

Figure 6. An Alternative "Physics Based" View of a Thermal System

Off-Grid (Remote) Energy System Alternatives

When this exercise started, solar, wind, and bio-mass were thought to be most promising, and many of the alternatives that ended up as most promising were not on the initial list. The “blocking” technology that would prevent from installation any of these alternatives, if they were practical, is the lack of any local grid power quality control and synchronization capability to integrate with the local grid. While many private-sector firms are working on alternative energy options, none appear to be working on a solution to the local grid integration and control issue.

In this example, one of the expectations was that alternate forms of energy which were not expected to be widely available were not to be considered; so alternatives such as tidal and low head dams were dismissed, but others that were novel or not expected to be suitable but for which there was no specific reason to exclude them remained on the list, and, surprisingly, some made the final cut. See Figures 7–9. Table 1 summarizes the significant differences in understanding of the options, as a result of the analysis. Insights gained during the process had a significant effect on the S&T investment strategy.

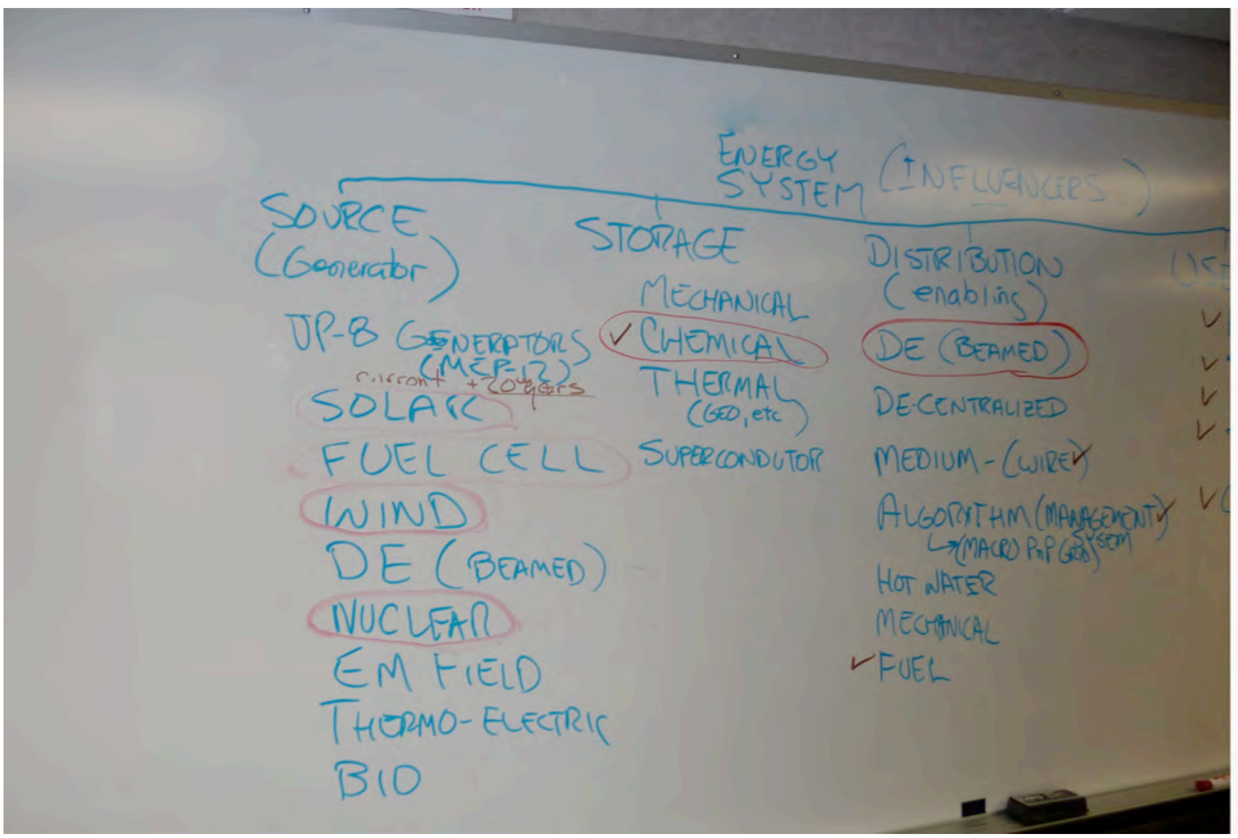

Figure 7. First pass working with a group of SMEs on creating a WBS.

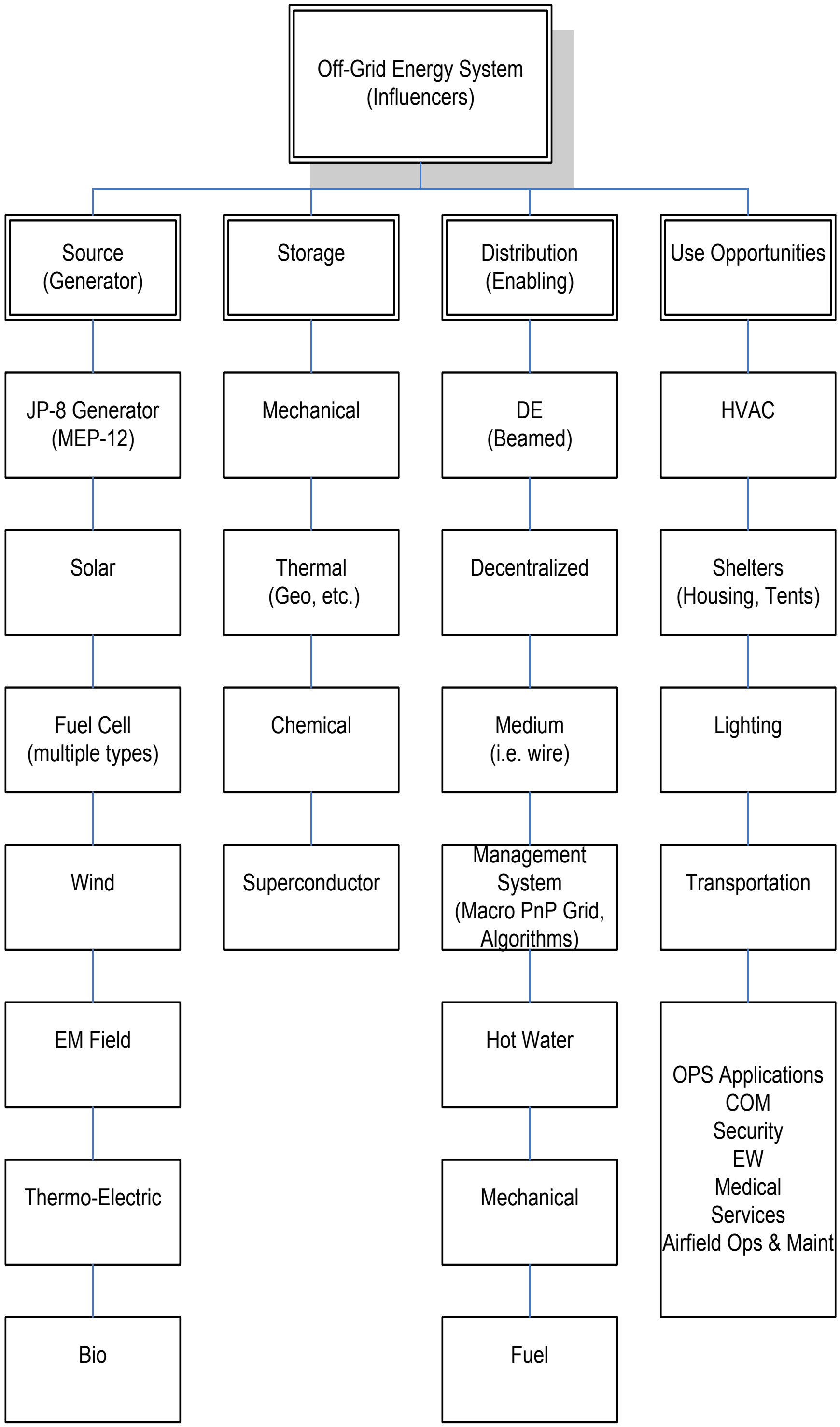

Figure 8. Influencers of Off-Grid Energy Systems

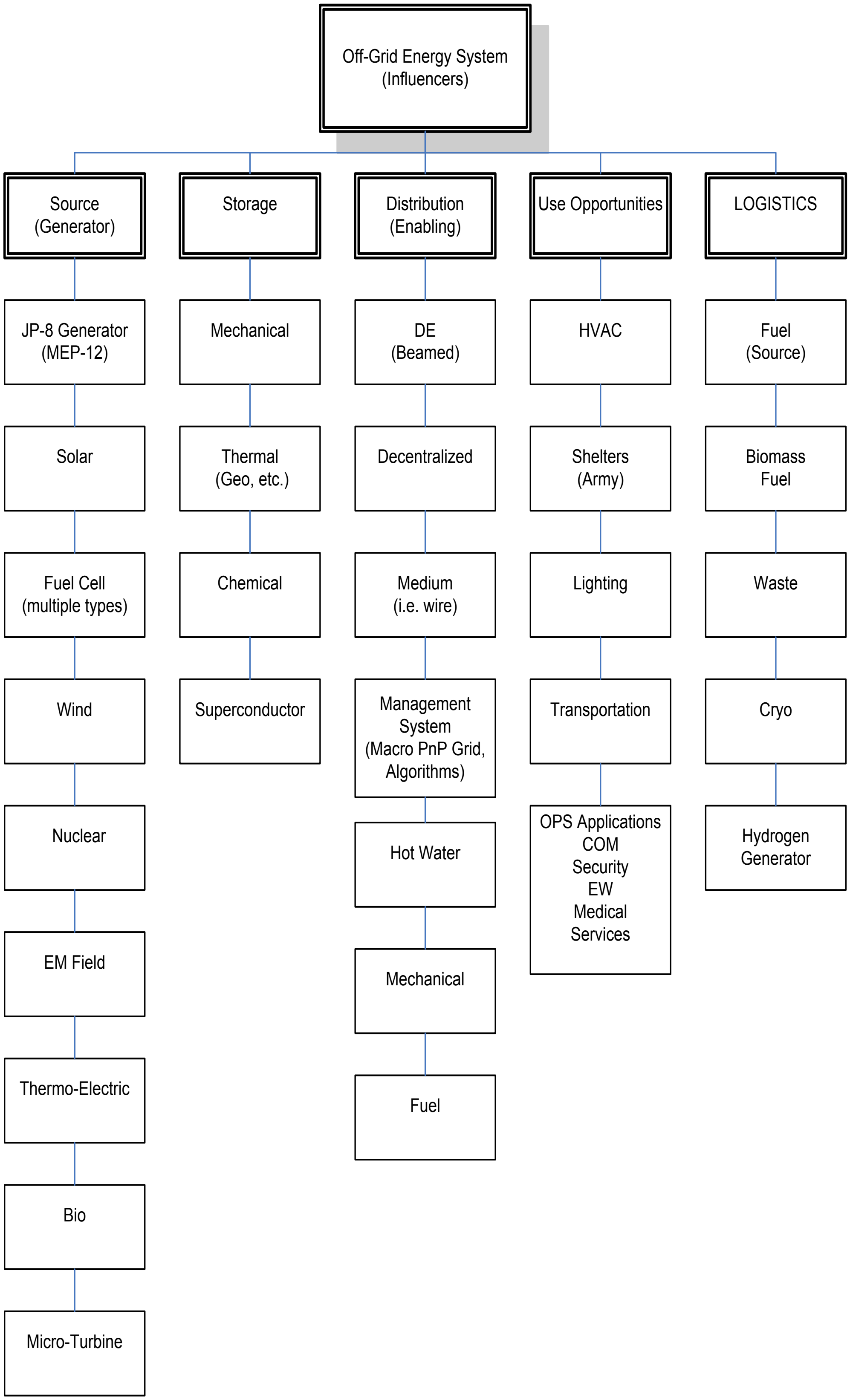

Figure 9. Influencers of Off-Grid Energy Systems

Table 1. Before and After SE Analysis

BEFORE (preliminary thoughts)	AFTER
Micro Turbines immature, limited utility	Mature technology, multiple commercial vendors, efficient, quiet, near drop-in
Power integration and management is a necessary evil largely addressed commercially	Critical enabling technology partially addressed commercially, required regardless of power source including local grid
Fuel cells (type not distinguished) very efficient, perhaps when mature a small panacea	PEM type dismissed as inadequate for power, solid oxide type is quiet, but may not be inherently more efficient after power conversion, more promising with heat recovery but has many in-use limitations
Solar with thermal concentrator no on initial list	Emerging technology in commercial use in Europe
Nuclear package ruled out as not politically practical	Limited commercial development may change political acceptance, better understanding of benefits
Space based beamed energy not on initial list	Already under study by National Security Space Office
Photovoltaics assumed promising	Fails most criteria, huge costs and deployment problems
Biodiesel assumed promising	Fails most criteria, huge costs and deployment problems
Wind turbines	Fails most criteria, huge costs, cannot be air deployed

UAV System

UAV System design did not anticipate the difficulty flying in the National Air Space and agreeing on protocols and air space integration.

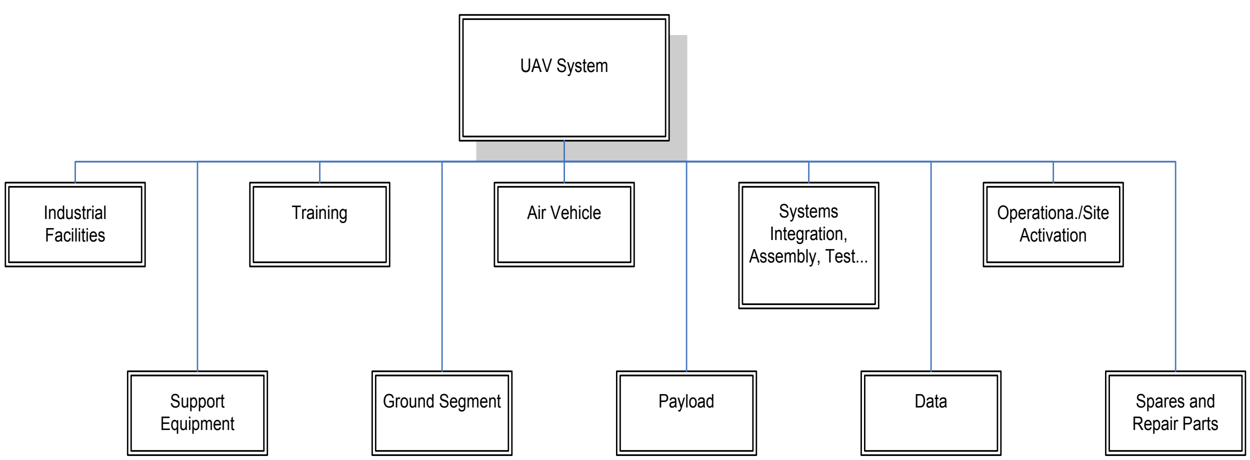

Figure 10. UAV System Top-Level WBS Based on MIL-HDBK-881A, Appendix H, H.3 Work Breakdown Structure

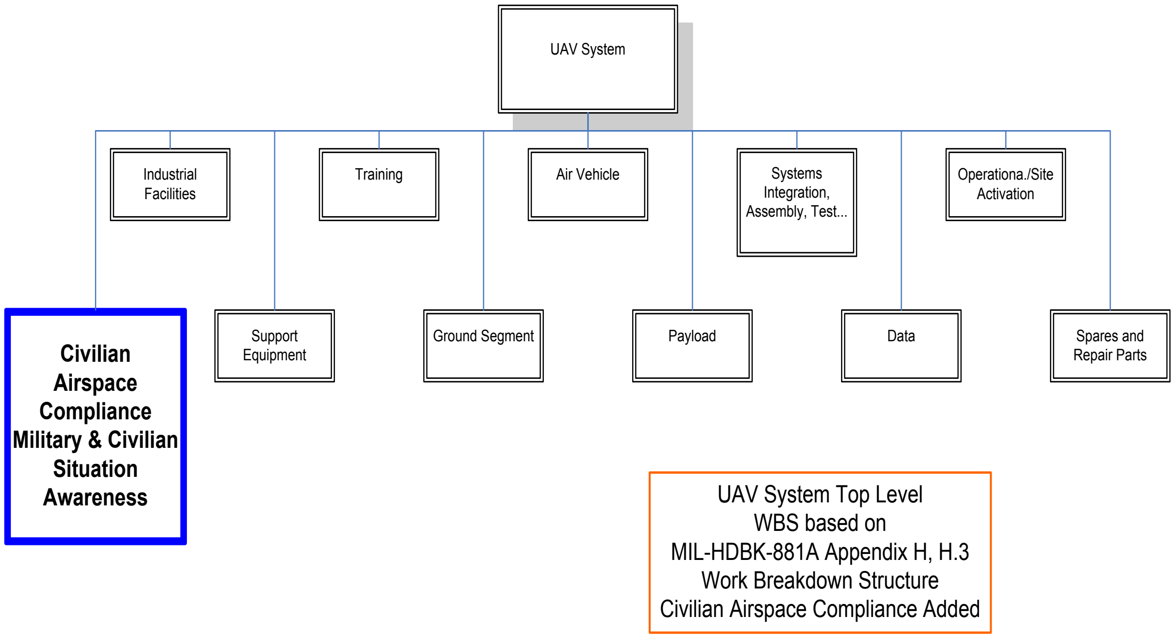

Figure 11. UAV System Top-Level WBS of Figure 10 with Civilian Airspace Compliance Added

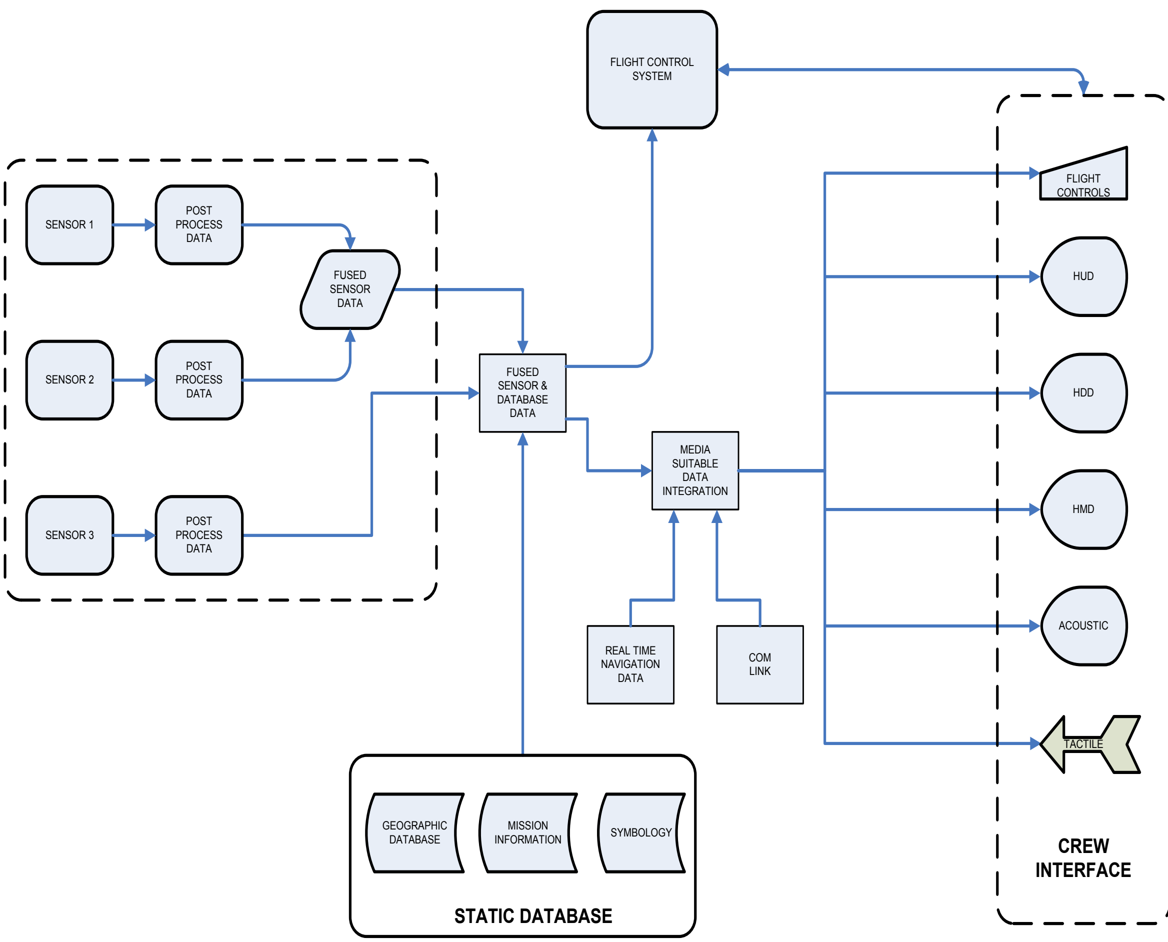

Figure 12. Notional Architecture for a Flight Control System; an Example of a Simple Architecture not in WBS Format

Robotic Manufacturing System

The initial WBS (Figure 13) was used by a robotic manufacturing systems company in their start-up phase. The company's initial customers were heavy weapons manufacturers. The founders had a vision and a technical background in manufacturing process development. They secured initial funding from angels, then venture capitalists, and finally they were majority owned by a Fortune 50 company.

After initial funding, they hired engineers with experience in robotics as well as an industrially experienced marketing guru who worked with prospective clients to develop requirements. The second WBS is what emerged (Figure 14) after customer input, and the capital requirements changed dramatically to reflect that. The difference added 18 months and $112 million in additional capital to the development cycle.

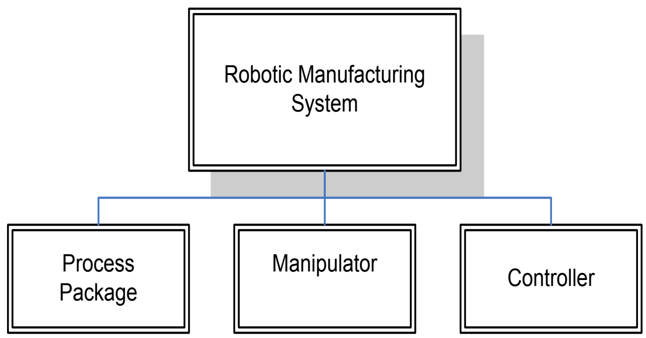

Figure 13. Start-up *Visionary* WBS for a Robotic Manufacturing System

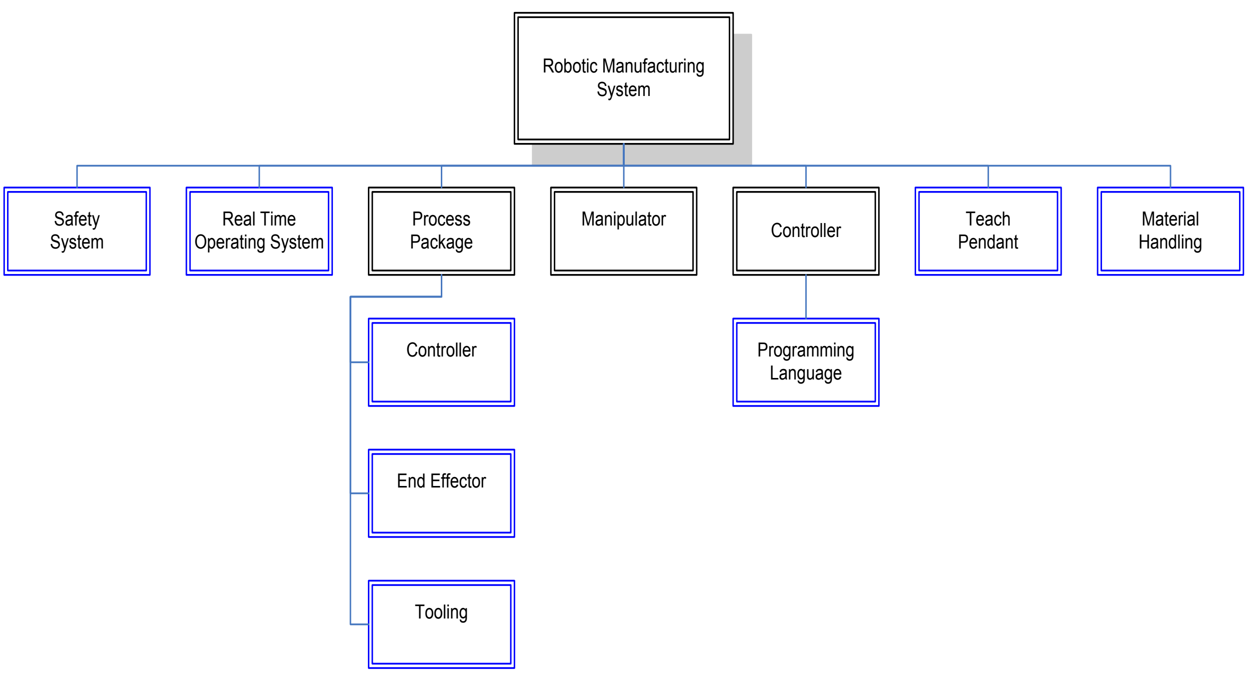

Figure 14. WBS Reflects a Practical Working Manufacturing System and the S&T Required to Deliver Those Systems

Conclusions

It is important to remember this whole paper applies to the Science & Technology phase of technology development. The more mature downstream phases require more semantic rigor, discipline and more expensive and sophisticated tools (as well as users). The hybrid WBS as described here is a simple, powerful, intuitive and highly leveraged first step in identifying a broader range of alternatives that may be necessary to deliver S&T to end users and capturing obstacles to eventually deploying S&T.

- The hybrid WBS captures key elements and not necessarily relationships between or among those elements.
- Hierarchical purity is unnecessary and the time spent may be counterproductive in the S&T stages if a "systems" view is in the future.
- It takes a team of Subject Matter Experts (SMEs) to create an effective hybrid WBS. There is a low probability that one person, particularly an S&T specialist, can create a valuable WBS. It is easy to create a perfunctory and useless WBS; it takes more work to provide game changing value.
- The WBS should be revisited frequently as the S&T matures through TRLs. The more interest in the S&T, the more important the WBS and its revelation of potential obstacles to applying the S&T.

[1] Fulghum, David A., Mysteries and Secrets: If you do not know about it, China Lake has it, Aviation Week & Space Technology, September 28, 2009, p66.