Science and Technology
Needs
for
[Air Force]
Modeling and Simulation

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ABSTRACT

Over the last 15 years, Modeling and Simulation (M&S) has grown considerably in capability and importance, especially for military purposes. Simulators for all kinds of sea, land, and air vehicles are used everyday. In some cases, simulators are linked to form teams, fighting with and against other simulators, computer-generated forces, and live forces operating their assigned weapon systems. Deployable trainers and other training systems are being increasingly fielded. Decisions about processes, weapons system design, training, rehearsal, analysis, experimentation, operational alternatives, and evaluation of systems are commonly (nearly always) assisted with simulation. Strategy, posture, and transformational documents throughout the Department of Defense (DoD) often mention the power of M&S or computer simulation to portray alternative futures and assist decision makers. Today, we link live forces (operating in their assigned weapons system) to virtual simulators (man-in-the-loop) and constructive (computer-generated) simulations; the Live-Virtual-Constructive (LVC) mix is now becoming commonplace, even though still difficult to set-up and execute. With limited military hardware assets in high demand and forces in high operational tempo executing the War on Terror, building a full team-of-teams combat environment short of war is most often completed with an LVC mix of available assets.

It is essential that the LVC environment be as agile and accurate as is necessary to support the task at hand, whether it is, for instance, force structure analyses, experimentation, test, or training. M&S has made so much progress in such a short time; yet, the Science and Technology (S&T) needs for M&S have remained fairly constant. M&S technologies, especially visualization, have vastly improved; yet progress on the technical underpinnings for M&S has stalled in many areas. For instance, M&S has made little to no progress over the last 15 years in portraying strategic and cascading effects on targeted systems or the cultural differences in behaviors between coalition and potential enemy forces. Delays in funding the S&T research to improve M&S tools for all purposes results in continued degradation of important M&S capabilities. If future portrayals of warfighting will rely, in part, on directed energy weapons, effects-based planning and operations, protecting and attacking critical networks, and considering human behavior and the will to fight, then M&S programs are deficient now in these areas, with insignificant related research destined for M&S programs. Lack of planned M&S research prior to initiation of M&S programs also degrades the programs' ability to fulfill the requirements in the capability/requirements documents, extends timelines, and increases costs.

AUTHOR BIO

Dr. Steven C. "Flash" Gordon is the Orlando Field Office Manager for Georgia Tech Research Institute. He served 26 years in the United States Air Force (USAF) as an aircrew member in the F-111, Director of Air Operations Centers, Air Staff Division Chief, and Head of the Department of Mathematical Sciences at the USAF Academy. He also served for 5 years as a government civilian as the Technical Director for the Air Force Agency for Modeling and Simulation. Dr. Gordon received a BS in Mathematics from Marymount College, MS in Human Development Counseling/Education from Peabody College, and an MS in Industrial Engineering/Operations Research and a PhD in Aeronautical and Astronautical Engineering from Purdue University.

INTRODUCTION

M&S is important in so many areas for commercial enterprises and DoD daily operations. For analysis of alternative futures, training/rehearsal of forces, and evaluation of systems and crews in dangerous environments, M&S is often the only convenient way to accomplish those missions. The LVC mix of assets and distribution of M&S environments throughout the world to groups in planning, training, or rehearsal allows those groups to immerse themselves in a realistic scenario and increase their readiness so that, when in combat, they feel like they have been there before, can anticipate enemy moves, and readily decide and act faster than enemy forces. M&S allows for inclusion of the full team of teams in an LVC mix for full-contact combat events even if most high-value, high-demand assets are not available live. M&S allows covert play and the ability to replay potentially deadly mistakes in a synthetic environment.

Of course, M&S is used widely in evaluation of alternatives, analysis, acquisition, and development test and evaluation (T&E) of new systems. As testing in a Joint mission environment is increasingly stressed, Operational T&E (OT&E) will use M&S to immerse new systems in full team of teams combat environments to see how they will perform in possible future Joint and Coalition combat. Assets that are otherwise unavailable live for the OT&E can be substituted by virtual or constructive replacements in an LVC mix. This will allow systems to be tested for effectiveness and suitability as rigorously as is possible with limited live forces and limited budgets. Clearly, the strengths of M&S to allow many runs at each test point should be leveraged. A sufficient number of runs at all test points can highlight trends in system performance, enable thorough synthetic testing throughout the desired performance envelope, and pinpoint key areas for focused live testing.

Depicting future combat scenarios is an honorable, yet frustratingly inexact undertaking. Therefore, it is valuable to admit two things. First, M&S is an approximation to the "real world" expected in combat. Second, any live (or especially a mixed LVC) event is an approximation of combat. It should also be noted that using too few live test runs can be as risky as any inexact set of M&S runs – either choice independently can lead to incorrect findings. With full coverage of LVC (M&S) runs and sufficient, focused live tests used together, leveraging the strengths of both, we can expect improved OT&E. However, because of its growing use and importance, M&S portrayal of expected battlespaces must be improved. Currently, M&S users have implemented work-arounds and added role-players to accommodate identified M&S shortfalls; yet, these stop-gaps may or may not be the long-term solution. Targeted investments for research aimed at improving M&S capabilities are essential. This paper provides the results of a 2005-2006 study performed for the Air Force Agency for Modeling and Simulation (AFAMS) [1]. The incorporated study tasks were to update the legacy Air Force S&T needs for M&S survey and to trace/anchor Air Force S&T requirements and capabilities for M&S to higher headquarters guidance and to similar sister-Service needs. For this study, early Air Force surveys on S&T needs for M&S from 1997 and 2001 [2, 3] were combined and updated, and the findings were circulated for review by Air Force researchers and M&S users in 2005 and 2006. The results reflect a combination of those legacy surveys as updated via field input. Ten areas for S&T improvement are proposed for underpinning M&S research, and, for the purposes of this report, S&T covers Basic (6.1), Applied (6.2), and some portion of Advanced (6.3) Research, as described in the Definition of Terms section, page 23 of this paper.

BACKGROUND

Changes in Warfighting

Aspects of how the United States conducts combat operations are changing [4]. The percent of precision munitions used in combat changed: Desert Storm (9%), Allied Force (35%). Enduring Freedom (64%), and Iraqi Freedom (68%+). Time-sensitive targeting also changed such that, during Enduring Freedom and Iraqi Freedom, 80% of targets were not preplanned, but were received by pilots inflight; during the first year of Iraqi Freedom, over 800 time-sensitive targets were struck. In Desert Storm, four aircraft were needed to "service" one target. Now, one aircraft on average will "service" four targets, generally precisely. It should be clear that the United States needs agility and flexibility in its military forces and decision support systems because of this changing warfighting environment and because enemies will attempt to counter any advantages and leverage any weaknesses they see in United States' systems or processes.

The anticipated national security environment for the United States includes a less predictable strategic environment, diminishing protections afforded by geography, growing asymmetric threats, diffusion of power and military capabilities to non-state actors, proliferation of chemical-biological-radiological-nuclear (CBRN) weapons, strengthening of regional threats, and emergence of a global threat [5-11]. Future enemies are watching the current events in the War on Terror, evaluating what is working against us and what is not, and thinking of new ways to counter or bypass our strengths. The United States military must anticipate and counter future enemy actions by seeking key technologies that facilitate increased speed of decision making and application of force; improve the agility of military tactics, techniques, and procedures to leap ahead of enemy tactics; and assist coalition forces to influence the enemy's will to fight prior to or early in conflict. It is expected that DoD will continue military transformation to stay ahead of future enemies. The scope of defense transformation includes DoD business processes, working relationships, combat operations, training transformation/Joint National Training Capability, and the Joint distributed environment for development and test [8, 12, 13].

Transformational capabilities will be pursued in information superiority (a key transformational enabler); integration of information from manned, unmanned, and space systems; network-centric operations; common, layered real-time picture of the battlespace; advancing the battlespace picture in time through delivering predictive mission-space awareness; seamless, Joint machine-to-machine integration; information assurance and information operations; and denial or control of adversarial C4ISR[1]. The future of warfighting includes a focus on speed, agility, precision, decision-making, reduced destruction, manipulation of the enemies' will, and knowledge supremacy.

Legacy M&S Requirements Studies

In 1997, Air Force Research Laboratory published a final report on enabling technologies for Air Force M&S [2]. Ten enabling technology areas were listed in this report: human modeling, resolution and validation management tools design, manufacturing and support technology,

[1] Command, control, communications, computer, intelligence, surveillance, and reconnaissance

model management tools, virtual reality technology, simulation design/experimental frame methodology, simulation paradigms, hierarchical simulation, knowledge compendium tools, and model abstraction.

In 1998 and 2001, the Air Force updated this enabling technologies survey to compose a listing of Air Force S&T Capability Needs in M&S [3]. These areas were modified from the 1997 report to focus the research areas more on warfighter needs in M&S, requesting M&S improvements in information/multi-level security, effects-based modeling/analysis, multi/mixed resolution integration and abstraction, human/organizational behavior and cognitive process representation, linking of real-time/live data/information into models/simulations, C4ISR representative and value evaluation (constructive), collaborative course of action (COA) development and analysis with mission rehearsal, representation and effects of non-traditional weapons, and data quality/manipulation/representation.

In November 2000, the Defense Modeling and Simulation Office (DMSO) surveyed Unified and Selected Supporting Commands on M&S needs [16]. Warfighters' common M&S needs gathered in the survey were multi-resolution and composable simulation environments, ease and cost of use, data availability and access, common operational picture (COP), staff training support, operational analysis tools, interoperability, human behavior modeling, verification and validation (V&V) support, multi-level security, resource repositories, reach-back support, and M&S education. The warfighter M&S needs listed above are not necessarily S&T investigation areas, rather S&T investigations may help M&S used by Combatant and Supporting Commands satisfy their needs in several of these areas. Some of the other areas listed may just need extra funding for development or insertion of existing technologies.

DISCUSSION

The Expanding Use of M&S

M&S provides the capability for humans to put themselves into an environment, a place, and/or a time to which they cannot otherwise go for various reasons. Humans tend to model and simulate naturally: they model what they are planning to do, thinking through tasks, especially hazardous ones, and evaluating potential dangers, considering mitigating options, before they tackle the task. In this way, it seems that M&S is human nature. When a traveler uses a mapping engine like MapQuest, he or she is able to look ahead at their travel route, envision options, vary map detail, and learn an efficient route of travel; a look ahead like this can make the trip less stressful and dangerous, and it should increase the traveler's capability to handle decisions about the hazards and uncertainty of the road. In a similar way, but using sophisticated computational support, M&S throughout DoD is used to reduce risk in new weapon systems and in operations. The Air Force uses M&S to evaluate future threats, program force structure and mix, equip forces for future wars and crises, and make decisions about current operations.

> "The joint synthetic environment will be a vehicle to develop future forces, concepts, systems, and doctrine where Air Force roles and missions will be appropriately and accurately represented." *The United States Air Force Transformation Flight Plan [13, page 28]*

Military M&S generally uses computational models, animated and interacting, as appropriate, to simulate anything from simple one-on-one interactions to the complexity of global war. Some arenas such as space exploration and nuclear detonations are areas where humans can not (for good reasons) go without the use of M&S; these use-cases rely primarily (perhaps totally) on M&S for decision support. Other arenas in DoD increasingly rely on M&S. When M&S deficiencies limit how well M&S depicts the expected reality, uncomfortable workarounds are used; these include simplifying assumptions, lower fidelity, neglected interactions, or extra role players. The workarounds generally limit realism and add subjectivity where it may not be helpful or effective.

> "A new generation of modeling and simulation (M&S) is needed to support concept development. M&S should promote experimentation and training by linking many types of simulations, from aggregate and detailed computer models, to simulators and man-in-the-loop hardware components." *Military Transformation: A Strategic Approach [8, page 26]*

It is expected that M&S increasingly will be relied on to depict complex systems-of-systems environments. Hence, M&S must represent all required aspects of the real world as faithfully as necessary for the purpose for which it is intended. M&S must be good enough. Good enough to predict future force structure equipment requirements and to design effective processes. Good enough to allow warfighters to effectively train, rehearse, and preview the next mission. Good enough to bend the enemy to our will; the enemy must be convinced that the United States' coalition holds every enemy target at risk at a time, at a place, and by a method of our choosing.

United States Marine Corps (USMC) S&T Needs for M&S [17]

The S&T needs for M&S listed by USMC include database correlation, cohesive mission rehearsal, rapid generation of urban landscape, constructive simulation wrap-around, C4I system of systems, training range networks, blended tracks, cognitive-physical integrated trainer, behavior modeling, realistic opposing forces (OPFOR) via augmented reality, passive collection of lessons learned, and human performance (tactical decision simulations, synthetic environments, cognitive performance enhancement)**.**

United States Navy S&T Needs for M&S [18, 19]

The S&T needs for the Navy are described in terms of capability gaps and planned research focus areas. The capability gaps for the Navy include manning to the edge (execute the future human capital strategy in manpower/personnel, training, and education), human systems integration, performance in networked environments, and understanding future opponents. A selection of the planned research areas for the Navy includes modeling, simulation, and human performance technologies; human systems integration and human-centered design; science of learning; team dynamics; curriculum/multimedia development; embedded training; deployable training; network-centric warfare; weapons simulation technologies; virtual technology and environments; human behavior modeling; synthetic cognition for team training; blur the line between training and decision support; and live/virtual/constructive integration.

United States Army S&T Needs for M&S [20]

The Army completed a report on S&T needs for battle command (BC) in November 2005. The thirteen high priority BC-related areas for S&T in M&S are listed as course of action systems, effects-based operations needs, systems models (communications, sensors, etc), information operations needs, human behavior representation models, guidelines for M&S applications, validation paradigms, systems of systems commonality methodology, embedded M&S, simulation composability integration, linking of BC to M&S, human-machine interface, and data concerns (acquisition, conversion, storage, LVC, and classification differences).

Overview of Current S&T Capability Needs for Air Force M&S

In March 2005, AFAMS initiated a study to update previous surveys of S&T needs for Air Force M&S, and this report summarizes that study "S&T Capability Needs for Air Force M&S" [1]. The findings were circulated and briefed to M&S researchers and users throughout the Air Force ant to support contractors on multiple occasions in 2005 and 2006. Ten consolidated S&T capability areas for Air Force M&S are proposed: multi-level security; effects-based modeling/analysis; human/organizational behavior and cognitive process representation; composability of models, components, and simulations; link live, virtual, and constructive (LVC) environments; command and control (C2) combat contributions; intelligence, surveillance, and reconnaissance (ISR) combat contributions; collaborative COA development and analysis; representation of non-traditional weapons; and modeling executable architectures.

It is assumed that the areas listed for S&T needs support the major initiatives and programs[2] that rely on M&S, including JNTC, DMO, ACE, AF-ICE, Testing in a Joint Environment, and QDR. Selected reference quotations are included to show higher-headquarters support for the warfighting asset/process being modeled or support for M&S for that specific purpose. The ten areas of S&T needs for Air Force M&S are described in the following pages, and additional information on each S&T area, including more relevant quotations, is included in reference [1].

1. Multi-Level Security

Statement of Need: The warfighter needs the capability to train as the coalition intends to fight, yet not compromise classified or sensitive information, processes, or systems. This will provide the capability to run distributed simulations at multiple levels of security simultaneously in an environment which supports users' needs and adheres to their differing security access privileges.

Specific Research Topics: Secure Simulation Gateways, Filtering, Guising, Renaming, Training Effectiveness, Intelligent Agents

[2] Joint National Training Capability (JNTC), Distributed Mission Operations (DMO) as the Air Force portion of JNTC, Air Force Constructive Environment (ACE) replacing the Air Force M&S Training Toolkit (AFMSTT), Air Force Integrated Collaborative Environment (AF-ICE) for accelerated acquisition, the Joint Test and Evaluation (T&E) initiative for testing in a Joint LVC mission environment, and the Quadrennial Defense Review (QDR) looking at future threats and future force postures, as appropriate.

DoD/Joint/Air Force References:

- "Multinational partnerships expand opportunities for coalition building through combined training, experimentation, and transformation."
  The National Military Strategy of the United States, page 26
- "Such information sharing requires multi-level security capabilities that allow multinational partners and other government agencies to access and use relevant information while reducing the probability of compromise."
  The *National Military Strategy of the United States, page 19*
- "Seamless multi-level security access will empower distributed command and control and provide increased transparency in multinational operations."
  The National Military Strategy of the United States, page19
- "A synthetic, realistic environment will allow better integration between units – coalition, joint, and Air Force." *The United States Air Force Transformation Flight Plan, page B-10*

Related Research: Trusted Network Guard (AFRL/HE[3] and DMOC[4]), CASPER (Northrop Grumman), Radiant Mercury Simulation Guard (USN), and Information Support Server Environment Guard (AFRL/IF[5])

Comments on Multi-Level Security*:* This S&T Capability Need for Air Force M&S is consistently listed as the most important need and has received steady attention and funding. Unfortunately, MLS and Information Assurance limitations have negatively impacted several coalition training events; yet, there continues to be a key need for coalition forces to train and rehearse as they intend to fight. MLS is particularly difficult in simulation environments because combinations of information in an LVC environment can be classified higher than individual parts of the information. Some advances in this MLS area will be driven by policy changes, not technology. The Air Force M&S lead for this research is at the DMOC with requirements and policy leads elsewhere in the Air Force. Progress has been made in using the Trusted Network Guard as a solution that does not unnecessarily reduce training value or training effectiveness. The need for progress in MLS is probably a shared requirement across the Federal government, including DoD, DHS, DOE, and the State Department.

2. Effects-Based Operations

Statement of Need: The warfighter needs the capability to portray cascading effects in future battlespaces to support all uses of M&S, including for wargaming, experimentation, analysis, acquisition, testing, training, rehearsal, and effective decisions in combat, to end conflict on our terms as efficiently as possible. This need includes the capability to portray effects of neglect or action on specific targets; specifically, functional and cascading effects will be portrayed for warfighters to be able to train as they intend to fight. This capability includes the portrayal of kinetic and nonkinetic weapons effects, the interdependency within and between target sets,

[3] Air Force Research Laboratory (AFRL) Human Effectiveness (HE) Directorate
[4] Distributed Mission Operations Center [of Excellence] (DMOC), Kirtland Air Force Base, Albuquerque, New Mexico
[5] AFRL Information Directorate (IF)

interrelationships between target systems, and modeling space superiority, situational awareness, and other space-based effects. Human behavior representation of individuals and groups, including political and cultural differences, must be included for realism.

Specific Research Topics: Asymmetric Forces, Target Systems' Modeling, Representing Multiple Orders of Effects, Target Support to Military Forces, Socio-Cultural Adversarial Modeling, Game Theoretic Adversarial Techniques

DoD/Joint/Air Force References:

- "…an effects-based approach provides U.S. commanders and planners with a new potential for attacking the elements of an enemy's will directly…"
  Military Transformation: A Strategic Approach, page 34
- "The emerging way of war is a unique approach to the conduct of joint warfare in the information age. Constructed around the fundamental tenets of network-centric warfare (NCW) and emphasizing high-quality shared awareness, dispersed forces, speed of command, and flexibility in planning and execution, it will result in U.S. forces conducting immensely powerful effects-based operations (EBO) to achieve strategic, operational, and tactical objectives across the full range of military operations."
  Military Transformation: A Strategic Approach, page 28
- **"**While US Armed Forces' will continue to emphasize precision, speed, lethality and distributed operations, commanders must expect and plan for the possibility that their operations will produce unintended 2nd- and 3rd-order effects."
  The National Military Strategy of the United States of America, page 5
- "The bottom line is to achieve effects on the battlefield with today's technology today rather than with yesterday's technology tomorrow. Achieving this aim requires collaboration among all the stakeholders in the acquisition process, to include the warfighter, funding, engineering, test, S&T, program management, industry, contracting, sustainment, and others." *The United States Air Force Transformation Flight Plan, page 23*
- "Future military operations will be effects based, rely on increased warfighter use of integrated on-demand sensor information, required more responsive time critical targeting, incorporate a growing arsenal of precision weapons, and utilize expanded nonkinetic options, including information operations."
  The United States Air Force Transformation Flight Plan, page 29

Related Research: Dynamic Air and Space Execution and Assessment (AFRL/IF); Commander's Automated Decision, Support Tools/Integrated Battle Command (DARPA); Multi-National Experiment 4, 27 February – 17 March 2006 (JFCOM); Theater Effects-Based Ops Korea ACTD (Army/USFK); United States Army (EBO)

Comments on Effects-Based Operations: This S&T need for further research in how to depict EBO in M&S is critical to ensure future M&S programs depict how Combatant Commanders intend to handle crises and prosecute combat operations. EBO is, in this sense, intended to include the capability to depict strategic and cascading effects in M&S. In an M&S-driven event, a decision-maker should see realistic second-order and third-order effects, at a minimum. Power grids degraded or destroyed must result in realistic effects on threat systems, fuel

pumping, population restiveness, fatigue in fielded forces, and other downstream effects. Communications grids degraded or destroyed should result in a realistic delay in command and control and some dependent degradation in performance and agility. ISR destruction should realistically result in poor decisions or decisions that are obviously independent of the real situation because it should not be known with clarity. These types of effects are not well-distributed through the synthetic environments used today, and current research in this area for the benefit of M&S programs is minimal to nonexistent. However, research of EBO in warfighting does exist and must be leveraged wherever possible. EBO overlaps several other S&T need areas for M&S, including Human Behavior Representation (HBR), Command-Control-Communications (C3) Contributions, and Intelligence-Surveillance-Reconnaissance (ISR) Contributions. The EBO S&T Capability Need area should be a common need across DoD and DHS.

3. Composability of Models, Components, and Simulations

Statement of Need: The warfighter needs the capability to develop appropriate databases and scenarios in hours not days or months and compose simulations quickly in order to wargame, experiment, analyze, acquire, test, train, rehearse, mission-preview, and make effective decisions in combat. This need includes the capability to generate databases quickly, construct necessary synthetic environments, and stipulate level of fidelity of simulation objects. It includes capability to vary the level of fidelity or detail of objects within a single simulation or between simulations, and it enables identification and extraction of essential information from lower level simulation products (high detail) for use in higher-level simulation products (low detail).

Specific Research Topics: Rapid Distributed Database Development, Joint/Coalition Integrated Synthetic Environment, Model Abstraction, and Mixed-Resolution Modeling

DoD/Joint/Air Force References:

- "A new generation of modeling and simulation (M&S) is needed to support concept development. M&S should promote experimentation and training by linking many types of simulations, from aggregate and detailed computer models, to simulators and man-in-the-loop hardware components." *Military Transformation: A Strategic Approach, page 26*
- "Standardized, interoperable, and readily available tools, which facilitate collaboration across a broad set of partners, are needed. Such collaboration tools can help us overcome the tyrannies of time and distance and enhance speed and precision in execution. Common operating pictures and common data packaging are essential."
  The 16th Chairman's Guidance to the Joint Staff-Shaping the Future, pages 9, 10
- "The Air Force M&S architecture will support analysis, acquisition, and training by linking together many types of simulations, from aggregate and detailed computer models, to pilots in live aircraft and simulators, to hardware components…The joint synthetic environment will be a vehicle to develop future forces, concepts, systems, and doctrine where Air Force roles and missions will be appropriately and accurately represented. The Air Force integrated M&S system will be manned and supported by experts and will represent the joint environment. It will also be affordable and efficient through reusable simulations with plug-and-play modules that have interoperability with joint, Service, and civilian environments."
  The United States Air Force Transformation Flight Plan, page 28

- "In a broad sense, long-term Air Force S&T is focused on…creating a rapidly composeable environment able to accurately replicate potential battlespace anywhere in the world through the use of rapid scenario generation tools and providing the ability to the warfighters in a timely manner." *The United States Air Force Transformation Flight Plan, page 77*

Related Research: Integration of Simulation with Real-Time Applications and Databases Phase II SBIR (AFRL/IFSD and ESC/CXI), and Ontological Composability of Models SBIR Phase I (AFRL/IFSD), Selectable Fidelity Synthetic Environment (EnvoyTek for DMSO), Joint Rapid Distributed Database Development (JFCOM), Joint LVC Data Translator (JFCOM), Rapid Construction of Urban Terrain Databases for Training (RDECOM), and FLAMES-Matlab-Simulink Integration (AFRL/VASA); Rapid Generation of Urban Landscape Database Correlation (United States Marine Corps), Common Tools for Interoperability (United States Navy), United States Army (simulation composability integration), and United States Army (Data Concerns)

Comments on Composability: M&S composability is the most important capability need for the warfighter to realize speed and agility in M&S tools. The warfighter needs M&S tools that are composed quickly for any purpose. Training and experimentation events take months and several planning conferences to compile data and decide on force laydowns; this is too expensive in terms of time, funding, and tempo. Sometimes in test, acquisition, analysis, or wargaming, the M&S user would like to substitute models of differing fidelity in a given simulation for evaluation of specific capabilities or sensitivity analysis; this is virtually impossible with the simulation environments of today. The Air Force often buys multiple models of specific weapons systems because of incompatibility of simulation environments and the fidelity needs of different users. If the Air Force could develop a technology to abstract the important aspects of a referent model of a weapon system and derive several derivative (abstracted) models from the referent, significant funding and time each year would be saved. Confidence in these derived models would be improved too. Every use of M&S confronts the issue of lack of composability and the inability of models of varying fidelity to run in most Air Force simulations. Commercial M&S environments, such as Matlab/Simulink, that are used worldwide, have made great strides in composability improvement, and these types of software show great promise in assisting DoD in M&S composability. Composability on M&S is a shared need for M&S across the Federal government.

4. Link LVC Environments

Statement of Need: The warfighter needs the capability to link live, virtual, and constructive simulations to produce realistic battlespace depictions for all uses including to wargame, experiment, analyze, acquire, test, train, rehearse, mission preview, and make effective decisions in combat**.** This need includes the capability to integrate LVC environments to exchange information and immerse participants. It includes the capability for operational systems to easily connect with distributed simulations and simulator systems.

Specific Research Topics: M&S over Grid, Compatibility of DIS/HLA with CTIA/TENA, Synchronization of Time Across Distributed Simulations, Human Systems Interfaces, Tracking Network Performance, and Joining Networks "On the Fly"

DoD/Joint/Air Force References:

- "The Joint National Training Capability (JNTC) will provide a real-world laboratory with the capability to conduct experiments that assess new doctrine, tactics, techniques, and procedures using live military forces against professional opposing forces in realistic combat conditions." *Military Transformation: A Strategic Approach, page 26*
- "JNTC will…prepare forces by providing…an integrated live, virtual, and constructive training environment with appropriate joint context that allows accurate, timely, and relevant training and mission rehearsal in support of specific operational needs."
  Department of Defense Training Transformation Implementation Plan, page 5
- "**Joint National Training Capability…**will provide an environment for realistic joint exercises against aggressive, free-playing opposing forces with credible feedback. The objective is to train as the Air Force will fight and increase the joint context of exercises through live, virtual, distributed, and constructive environments."
  The United States Air Force Transformation Flight Plan, pages 28, 29
- **"**The Joint National Training Capability is based on an integrated live, virtual, and constructive simulation environment that is available globally on a 24-hour basis, and linked to real-world command and control systems. The Joint National Training Capability can be used to train forces against a general threat, to conduct mission rehearsal against a specific threat, or to experiment with new doctrine, tactics, techniques, procedures, Joint Operational Concepts, and equipment."
  Department of Defense Training Transformation Implementation Plan, page 12
- **"**The Air Force has integrated live, virtual, and constructive training environments into a single training realm using a distributed mission operations (DMO) capability. JNTC will use this DMO capability to tie live training events with virtual (man-in-the-loop) play and constructive simulations….These types of integrated training operations reduce overall costs to the services while providing us yet another avenue to train like we intend to fight."
  United States Air Force Posture Statement 2004, pages 39, 40

Related Research: M&S environments for DMO and AF-ICE; JFORCES (ANG), Events run by DTOC (NGB) and DMOC, Advanced Concepts Event II (AFRL/DE), LVC Composability (AFRL/VASA), Joint LVC Data Translator (JFCOM), LVC Futures Concept Lab (RDECOM), and Joint Test and Evaluation Management (JT&E); United States Army (Data Concerns)

Comments on LVC Environments: The integration of LVC entities in a useable environment is very difficult. Mixing live, virtual, and constructive entities on the same common operational picture (COP), maintaining realism and safety, depicting smooth hand-offs as entities transition between LVC types, and maintaining dependable LVC environments are all technically challenging. Planning an LVC event -- with all the fall-back options of which entities are live, virtual, or constructive and when -- and integrating the different systems to portray on one COP, maintaining realism and safety, takes a significant staff and a long planning cycle. As we transition to LVC training, rehearsal, acquisition, and test environments, to get the most complete and realistic environment short of war, the integration of LVC in a useable environment must become more user-friendly and agile/responsive. This research area is connected to the MLS Capability Need in the sense that LVC environments present an increased

challenge to MLS, and MLS considerations impact LVC planning. The LVC need for M&S also overlaps the M&S composability need. This should be a shared need across DoD and DHS.

5. Depiction of C3 Contributions

Statement of Need: The warfighter needs the capability to depict command, control, and communications in M&S for all uses including to wargame, experiment, analyze, acquire, test, train, rehearse, mission preview, and make decisions about networks to protect and attack, including methods and processes used. This M&S need includes the capability to portray the activities to protect and leverage coalition C3 and their composite network, and to exploit, diminish, or destroy enemy C3 assets and networks. For this capability, accurate representation of C3 assets and networks, contributions, and processes in M&S is essential. In particular, there is a need to better represent the value of global situational awareness (including OneAF-OneNet) and to reflect its effect on operations.

Specific Research Topics: Modeling C3 and Network Contributions to Red, Blue, and Grey Forces, Impacts of C3 and Network Degradation, and Cascading Effects

DoD/Joint/Air Force References:

- "Network-centric operational capability is achieved by linking compatible information systems with usable data. The functions of sensing, decision-making, and acting – which often in the past were built into a single platform—now can work closely even if they are geographically distributed across the battlespace."
  The National Defense Strategy of the United States, page 14
- "Achieving the full potential of net-centricity requires viewing information as an enterprise asset to be shared and as a weapon system to be protected."
  Quadrennial Defense Review Report, page 58
- "NCW [Network-Centric Warfare] will provide increasing return on investment by providing our most important resource – our people – the high quality shared awareness necessary to speed mission accomplishment. NCW capabilities will accelerate our ability to know, to decide, and to act…" *Military Transformation: A Strategic Approach, page 19*
- "At its core, C2 is about decision making.…effective C2 will be achieved through collaboration that enables cohesive teams, regardless of location, to develop a shared understanding of commander's intent and the battlespace, thereby enabling better informed decision-making." *Operational Implications of Effects-based Operations (EBO), page 5*

Related Research: ISR Capabilities Analysis with COSMOS (AFRL/XPZ), Joint C2 (JFCOM), and Modeling C2 for Analyses (AFRL/VASA and Johns Hopkins APL)**,** United States Marine Corps (C4I Systems of Systems), United States Navy (Network Centric Warfare), and United States Army (systems models for communications, sensors, etc.)

Comments on C3 Contributions: For virtually all M&S programs, the depiction of the contribution of C3 is deficient. Today's M&S tools seldom, if ever, (but always incompletely) portray the contribution of degraded command and control toward enemy or coalition warfighting capability unless it is handled by role players or artificial M&S inputs. The value of

C3 to friendly and enemy forces and decisions/actions is not included in M&S and often not exercised in simulation events; in fact, the cascading effects of disruption, destruction, denial, or contamination of the C3 are not modeled directly. Forces must train and rehearse as they intend to fight, and force structure must be determined using the best available M&S of C3. This M&S need for C3 representation also supports the EBO need and is somewhat dependent on ISR and HBR representation needs. Research in C3 for warfighting must be leveraged wherever possible. This S&T Capability Need for the Contribution of C3 in M&S should be a shared need across the Federal government.

6. Depiction of ISR Combat Contributions

Statement of Need: The warfighter needs the capability to depict intelligence, surveillance, and reconnaissance combat contributions in M&S for all purposes including wargaming, experimentation, analysis, acquisition, test, training, rehearsal, mission preview, and decision support so that coalition assets are adequately defended and hostile assets are at risk at a time and by a means of coalition choosing. This M&S need includes the capability to portray activities to protect and leverage coalition ISR and to exploit, diminish, or destroy enemy ISR. For this capability, accurate representation of ISR contributions and processes in M&S is essential. In particular, there is a need to better represent the value of global situational awareness and to reflect its effect on operations. This includes improvement in modeling effects and representation of the impact of space support and new defensive/offensive space technologies.

Specific Research Topics: ISR Contributions to Target ID, Modeling ISR Assets and Interactions, and ISR Contributions to Force Employment

DoD/Joint/Air Force References:

- "Decision superiority…necessitates new ideas for developing architectures for … intelligence, surveillance and reconnaissance assets that provide knowledge of adversaries."
  The National Military Strategy of the United States, page 19
- "Make the enemy fight blind, deaf, and dumb by disrupting its C4ISR."
  The United States Air Force Transformation Flight Plan, page 78
- "Network-centric operational capability is achieved by linking compatible information systems with usable data. The functions of sensing, decision-making, and acting – which often in the past were built into a single platform—now can work closely even if they are geographically distributed across the battlespace."
  The National Defense Strategy of the United States, page 14
- "The joint force will use superior intelligence and the power of information technologies to increase decision superiority, precision and lethality of the force. A networked force capable of decision superiority can collect, analyze and rapidly disseminate intelligence and other relevant information from the national to tactical levels, then use that information to decide and act faster than opponents."
  The National Military Strategy of the United States of America, page 16
- "PBA is an integrated process involving Intelligence Preparation of the Battlespace, Weather Operations, Target Development, ISR Strategy and Planning, ISR Employment, and Assessment that provides the commander a multidimensional understanding of the

battlespace in time, space, and effect, regardless of the adversary, location, weather, or time of day." *The United States Air Force Transformation Flight Plan, page 55*

- "Improving C4ISR provides greater asset capability, shorter kill cycles, and quicker battle damage assessments. The concepts of parallel warfare and EBO depend greatly on measuring opponent reactions, identifying opposing capabilities, and frustrating efforts to protect key infrastructures. C4ISR gives commanders the ability to respond quickly to opportunities to destroy critical enemy assets."

  The United States Air Force Transformation Flight Plan, page B-10

Related Research: ISR Capabilities Analysis with COSMOS (AFRL/XPZ), Representation of ISR and Fusion (AFRL/IF), and Space Threat Assessment Testbed (AFRL/IFSD); United States Army (systems models for communications, sensors, etc.)

Comments on ISR Combat Contributions: This need for ISR depiction in M&S acknowledges that the contributions of the "eyes and ears" for enemy and coalition forces are not depicted in M&S for most (all) purposes. ISR resources are modeled in these simulations; yet the impact of having or not having ISR feeds or products is not, and the cascading effects of disruption, destruction, denial, or contamination of the ISR flow are not modeled. Role players, pre-canned inputs, or assumptions are generally used as workarounds. Research of ISR for warfighting must be leveraged wherever possible. This S&T Capability Need for the Contribution of ISR in M&S should be a shared need across the Federal government.

7. Collaborative COA Development and Analysis – M&S Goes to War

Statement of Warfighting Need: There is a growing need for M&S used as a visualization and decision support tool in combat; the warfighter needs the capability to visualize future battlespaces and COAs, play-out options, and understand consequences of coalition and hostile actions. This M&S need includes the capability to exploit M&S as a powerful tool to visualize current and future states of friendly and enemy orders of battle, help commanders decide how to control friendly forces, and predict consequences of anticipated actions or inaction.

Specific Research Topics: Analysis of Alternatives for Commanders' M&S Toolset, Human Systems Interfaces, and Real-Time Continuous Updates of M&S Databases

DoD/Joint/Air Force References:

- "Decision superiority requires new ways of thinking about acquiring, integrating, using and sharing information…Commanders must communicate decisions to subordinates, rapidly develop alternative courses of action, generate required effects, assess results and conduct appropriate follow-on operations.

  The National Military Strategy of the United States, page 19

- "In all cases, we will seek to seize the initiative and dictate the tempo, timing, and direction of military operations." *The National Defense Strategy of the United States, page 8*

- "Bringing decisive capabilities to bear increasingly will rely on our capability to harness and protect advantages in the realm of information."

  The National Defense Strategy of the United States, page 14

- "Commanders must develop plans that ensure they retain the agility to contend with uncertainty, apply effects decisively and integrate actions…."
  The National Military Strategy of the United States of America, page 7
- "Decision superiority – the process of making decisions better and faster than an adversary – is essential to executing a strategy based on speed and flexibility. Decision superiority requires new ways of thinking about acquiring, integrating, using and sharing information."
  The National Military Strategy of the United States of America, page 19
- "A decision superior joint force must employ decision-making processes that allow commanders to attack time-sensitive and time-critical targets. Dynamic decision-making brings together organizations, planning processes, technical systems, and commensurate authorities that support informed decisions."
  The National Military Strategy of the United States of America, page 20
- "Speed is critical to our future success. Improved speed of action and decision is one of the more important services we can provide our Nation's leaders and those we support in executing the operational missions of the department. Improved speed of decision is not the same thing as making hasty decisions. Quality assessment is a critical element of an efficient decision cycle. We must discriminate between speed and haste."
  The 16th Chairman's Guidance to the Joint Staff-Shaping the Future, page 8
- "The next frontier of transformation is embedding decision-support tools for the commander." *The United States Air Force Transformation Flight Plan, page B-11*
- "…developing and embedding new and improved Decision Support Tools will allow commanders to leverage advantages in communications and intelligence to maintain decisive advantages over future enemies. Of course, fielding these systems will require applicable training programs as well as executable plans and implementing tools that can keep pace."
  The United States Air Force Transformation Flight Plan, page B-10
- "Decisions to apply force in multiple, widely dispersed locations require highly flexible and adaptive joint command and control processes. Commanders must communicate decisions to subordinates, rapidly develop alternative courses of action, generate required effects, assess results and conduct appropriate follow-on operations."
  The National Military Strategy of the United States of America, page 19

Related Research: Dynamic Situational Analysis and Prediction (AFRL/IF), Dynamic Strategy Development Tool (AFRL/IF), Grid of Grids for Information Management Phase II SBIR (AFRL/IFSD), Knowledge-Based Technologies to Support Predictive Mission Awareness Phase I SBIR (ESC PEO-DAC), Augmentation-Based Approaches to Enhance Time-Critical Dynamic Decision-Making Phase I SBIR (ESC PEO/DAC), Uncertainty Visualization for M&S of Complex Systems Phase I SBIR (ESC PEO/DAC), and SplashNotes Phase I SBIR (AFRL/IFSD), Commander's Automated Decision Support Tools/Integrated Battle Command (DARPA), and Embedded Combined Arms Training and Mission Rehearsal (RDECOM), United States Marine Corps (Tactical Decision Simulations), United States Navy (Blur the Line Between Training and Decision Support), and United States Army (Course of Action Systems)

Comments on COA Development and Analysis: M&S for Collaborative COA Development and Analysis is the research area that represents a relatively unexplored use for M&S. Even though M&S, in some form, has been used in every recent military campaign, especially in the

lead-up to the execution order, the use of M&S to support ongoing military operations has not been institutionalized. If M&S is developed to be useful to Commanders at the operational level of war, it will be incorporated in training and rehearsal programs, and then staffs will be inclined to use M&S during combat operations. M&S can be used to visualize and animate military movement orders, look at friendly and enemy courses of action, evaluate alternatives, and help the Commander make better informed decisions. M&S for Collaborative COA Development and Analysis will help Commanders make better decisions, saving lives, time, funding, property, and other national assets. M&S that is truly useful to the operational Commander must, as accurately as is necessary, reflect EBO, HBR, and C3 and ISR contributions, and it must be agile/composable. This S&T need for M&S should be a shared need across the Federal government. DHS may realize benefit from this capability in other ways such as visualizing predicted natural disasters to inform and motivate populations at risk.

8. Representation of Non-Traditional (NonKinetic) Weapons

Statement of Warfighting Need: The warfighter needs the capability to depict all options at coalition disposal, including all types of weapons, effects, and consequences. The M&S need to depict Non-Traditional Weapons (IO, DEW, Chem/Bio)[6] includes the capability to depict nonkinetic weapons in simulations and represent the direct and indirect effects of nonkinetic weapons. This capability will provide decision makers with M&S tools to explore emerging concepts, acquire systems that use these types of weapons, and train warfighters in the totality of weapon systems available to them.

Specific Research Topics: Modeling Nonkinetic Weapon Employment, Modeling Nonkinetic Weapon Effects on Targets, and Human Behavior Representation

DoD/Joint/Air Force References:

- "The Joint Force requires the ability to conduct information operations…"
  The National Military Strategy of the United States of America, page 60
- "Future military operations will be driven by an effects-based focus, increased warfighter use of integrated on-demand sensor information, more responsive time critical targeting, a growing arsenal of precision weapons, and expanded nonkinetic information operations options." *Distributed Mission Operations Implementation Plan, page 3*
- "The Joint Force requires the ability to conduct information operations…."
  The National Military Strategy of the United States, page 60
- "Cyberspace is a new theater of operations. Consequently, information operations (IO) is becoming a core military competency…Developing IO as a core military competency requires fundamental shifts in processes, policies, and culture."
  The National Defense Strategy of the United States, page 13
- "The objective is to train as the Air Force will fight and increase the joint context of exercises through live, virtual, distributed, and constructive environments. This involves not

[6] Information Operations (IO), Directed Energy Weapons (DEW), Chemical (CHEM), Biological (BIO), and others

only modernizing the integration of space and information operations in training ranges, but also planning for their sustainment to meet future test and training missions…"

The United States Air Force Transformation Flight Plan, page 29

Related Research: Representation of Next Generation Weapons (AFRL/DE and AFRL/VASA), United States Navy (Weapons Simulation Technologies) and United States Army (Information Operations Models)

Comments on Representation of Non-Traditional Weapons: M&S that accurately includes all nontraditional (nonkinetic) weapons available to operational Commanders is essential for experimentation, wargaming, analysis, acquisition, test, training, rehearsal, and decision support to operations. M&S that is used to look at future battlespaces must accurately portray future friendly and enemy weapons. In particular, M&S that is used for collateral damage estimation must incorporate directed energy and other nonkinetic weapons for future campaigns. For nontraditional weapons such as IO, this S&T Capability Need is related to HBR because IO is designed to alter the behavior of the targeted individuals. This S&T Capability Need should be a shared need across DoD.

9. Human/Organizational Behavior and Cognitive Process Representation

Statement of Warfighting Need: The warfighter needs the capability to depict coalition and enemy human behavior and the will to fight so that effects-based operations, networks, and the decision-support tools can be effectively exploited to manage the will and capability of the enemy to fight. This M&S need includes the capability to improve M&S technology to accurately represent human thought processes and behavior patterns. Factors include stress, fatigue, training, education, and cultural differences. This effort will develop semi-automated forces and intelligent simulation agents that behave as accurately as possible. "Smart" friendly and opposition forces will help improve the realism of combat effects, reduce exercise control staffs, and assist data mining/management.

Specific Research Topics: Algorithms for Depicting Human Behavior, Representing Cultural Differences, Effects of Stress, Learning Algorithms, and Cyber Mentors

DoD/Joint/Air Force References:

- "However, the objective of an effects-based strategy, including the actions that advance it, is not to win a military campaign or a war through the physical attrition of the enemy but to induce an opponent or an ally or a neutral to pursue a course of action consistent with our security interests. The question of will is fundamental to both the symmetric and asymmetric models of conflict…." *Military Transformation: A Strategic Approach, page 34*

Related Research: Asymmetric Adversary Tactics and Strategy Generation Phase II SBIR (AFRL/IFSD and ESC/CXI); AOC Simulation Interface and Intelligent Mission Controller Node (Gestalt for AFM&STT; Uncertainty Visualization Phase II SBIR (AFRL/IF and ESC), Real Time Adversarial Intelligence Decision-making (DARPA), and Behavior Modeling in FLAMES (AFRL/VASA), United States Navy (Human Behavior Modeling, Augmented Cognition, Human Performance Technology), United States Marine Corps (Behavior Modeling, Realistic OPFOR

via Augmented Reality, Understanding Our Opponents), and United States Army (Human Behavior Representation models)

Comments on Human/Organizational Behavior Representation: The S&T Capability Need for HBR is important because progress in this area will lead to progress in other S&T areas such as EBO and Depiction of C3 and ISR Contributions and will improve M&S for Collaborative COA Development and Analysis. The ultimate goal of warfare (and, hence, of M&S) is to bend the enemy to our (coalition) will. Therefore, M&S used to portray future battlespaces, evaluate new weapons or processes, or provide decision support to our Commanders must be able to portray friendly (protected) and enemy (targeted) behaviors. A very small HBR program like IMCN has resulted in savings of thousands of labor hours each year and provided improved accuracy for M&S users. Where limitations exist in what can be modeled with today's technology, these must be identified and workarounds implemented. This S&T Capability Need should be a shared need across the Federal government.

10. Executable Architectures

Statement of Warfighting Need: The warfighter needs agile M&S tools that are engineered to work on the global grid and function swiftly and effectively in a networked system of systems environment. This M&S need includes the capability to develop tools for analysis and evaluation of architectures, maintain DoD Architectural Framework compliance, and implement the known theoretical academic research on the mathematics underlying the executable models, including finite state models, colored Petri nets, queuing, and Markov chains. Researchers need the capability to specify an integrated operational/systems architecture of a project, specify operational scenarios and system design parameters, compute measures of performance/merit, identify bottlenecks, and perform sensitivity analyses.

Specific Research Topics: Maintaining Time Ordering, Interconnections of Discrete and Continuous Event Simulations, and Integration of Architecture Design and Evaluation Processes into the Systems Engineering Process

DoD/Joint/Air Force References:

- "Integrated architectures describe in greater detail the relationship between the tasks and activities that generate effects on enemy forces and supporting operations. They identify where operations intersect and overlap and provide details on interoperability requirements. The architectures include not just material solutions but also doctrine, organization, and training requirements. These architectures will be used to prioritize capabilities based on their contribution…" *Military Transformation: A Strategic Approach*
- Common operational, technical, and system architectures will be developed and adopted to allow integrated live, virtual, and constructive simulations to interoperate regardless of Service provider." *Department of Defense Training Transformation Implementation Plan*

Related Research: Integration of Model Architectures in Multiple Representational Languages Phase II SBIR (AFRL/IFSD and ESC/CXI), and Semantically Correct Interoperability of Executable Architectures Phase I SBIR (ESC PEO/DAC)

Comments on Executable Architectures: This S&T need for M&S represents an area that was not included in previous S&T surveys. Partly due to higher-headquarters guidance and partly due to advances in technology, executable architectures are being developed, although research is needed to make them more useful and effective and to integrate them into M&S for systems engineering. This S&T Capability Need should be a shared need across the Federal government.

CONCLUSION

This paper summarizes ten areas where S&T investments are needed to improve M&S capabilities. The description of the ten areas also includes references to related sister-Service M&S needs and selected references from higher-headquarters guidance. Related S&T requirements and research are also listed. M&S will continue to grow in capability, importance, and usefulness; and initiatives across all facets of the defense enterprise will increase the use of M&S in analysis, experimentation, wargamming, training, rehearsal, test, and acquisition. For instance in T&E, M&S will be used in robust LVC environments to help portray future Joint wartime missions for evaluation of effectiveness and suitability of systems; the combination of LVC environments for full exploration of the test envelop and selected live events for evaluation of key portions of the test envelop will be very powerful. Furthermore, the use of M&S for decision support to homeland security and military operations will increase, with M&S used to predict and portray coalition and enemy actions and positions. M&S will increasingly become an operational tool to aid coalition decisions and persuade the enemy to bend to coalition will, prior to or during combat. It will be important for M&S to reflect the anticipated battlespaces or crisis environments as faithfully as is necessary. Similarly important is the need to share M&S improvements, techniques, databases, and scenarios across all user communities to save time, funding, and tempo. Improving M&S where needed will save valuable national resources and help avoid the pitfalls of the past. Improving M&S is essential to national security – to reduce risk and build on our advantages over potential enemies – and it requires measured and well-engineered improvements over time.

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DEFINITION OF TERMS

Modeling – Developing a representation of an object, system, or process

Simulation – Changing the state of model(s) over time or through events and/or representing pertinent interactions between models

Science and Technology (S&T) – Assumed to be Basic Technology Research (6.1) and the early portions of Technology Development (6.2/6.3) needed to correct deficiencies in Air Force M&S to support current and predicted needs. The relationship between research funding and technology readiness levels (TRL) is Basic Technology Research (6.1/6.2, TRL1-2), Technology Development (6.2/6.3, TRL 3-5), Operational Capabilities (6.4-6.7, TRL 6-9).

6.1 Funding – Basic research, which is inherently, but decreasingly, high risk, long term, perhaps 5 years before transitioning to 6.2 applied research, programs, or ceasing. Results may be applied directly to military systems, especially with emphasis on military relevance.

6.2 Funding – Applied research, exploratory development, enabling technology; work does not have a direct set of users, but has broad base of potential customers. This research is described by observers inside and outside the R&D community as the “seed corn" for future work.

6.3 Funding – Advanced research; advanced development expenditures are largely for industry contracts devoted to transitioning technologies into weapons. Transitioning from 6.2 to 6.3 is not well defined but depends on having a customer and a capability ready to be turned into a product; eventually, advanced research funding is handled by program funding.

TRL 1: Basic principles observed and reported. Scientific research begins to be translated into applied research and development. Includes paper studies of a technology’s basic properties.

TRL 2: Technology concept and/or application formulated - invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions.

TRL 3: Analytical and experimental critical function and/or characteristic proof-of-concept - active research and development is initiated. This includes analytical studies and laboratory studies to physically validate predictions of separate elements/components of the technology.

TRL 4: Component and/or breadboard validation in laboratory environment – basic technological components are integrated to establish that they will work together. This is relatively “low fidelity” compared to the eventual system. Lab integration of “ad hoc” hardware.

TRL 5: Increased fidelity component and/or breadboard validation in relevant environment. The basic technological components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment. High fidelity laboratory component integration.