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A Proposed 2025 Ground Systems "Systems Engineering" Process

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The U.S. Army's mission reflects a strong impetus to provide flexible and adaptable ground vehicles that are rapidly fieldable. Emerging manufacturing technology, such as three-dimensional (3D) printing, is making mass customization possible in commercial industry. If the Army could produce tailored military ground vehicles that incorporate mission-specific tactics, it would outperform generic systems. To produce such systems, a new systems engineering (SE) process should be developed. Virtual environments are central to the proposed SE/2025 process because they provide a sandbox where soldiers and engineers might directly collaborate to codevelop tactics and technologies simultaneously. The authors' intent is to describe how ground vehicle systems might be developed in 2025 as well as to describe current efforts underway to shape the future.

« Image designed by Diane Fleischer

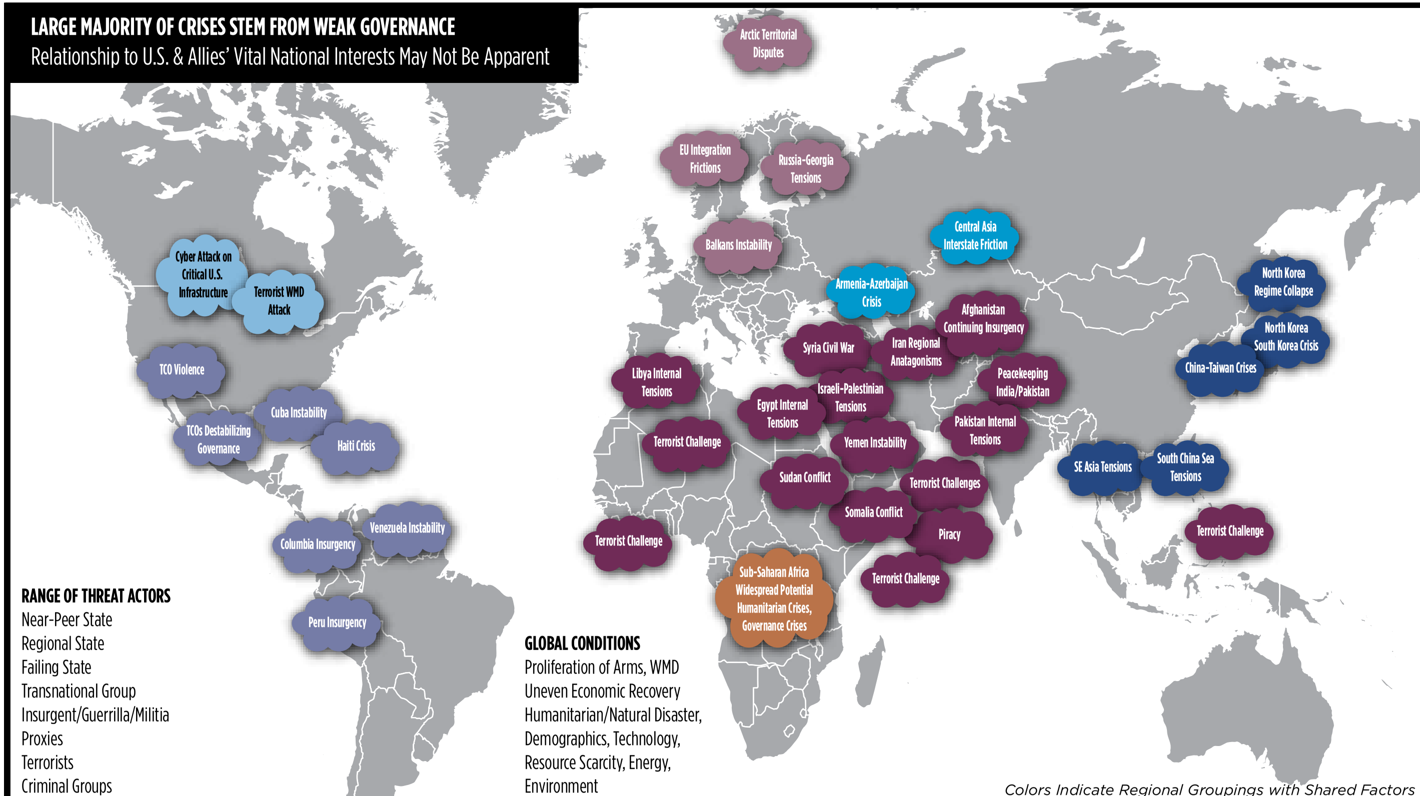
In the past, the United States Army has been able to anticipate capability gaps and needs based on a relatively static threat, but that model has disintegrated over the past two decades (United States Army, 2013). Figure 1 illustrates pictorially the range and complexity of the current defense landscape. Constantly shifting mission requirements will likely remain the norm in the foreseeable future. As such, combatant commanders will need ground vehicles, including robots that are flexible, adaptable, and rapidly deployable. Additionally, some of the most promising future warfighting technologies, such as robotics, computing, and advanced communications, will be readily available for non-State actors and nations to purchase from the global commercial market. To maintain a military advantage, the United States needs to develop a process that enables the lucid and rapid production of mission-tailored platforms that do not rely solely on cutting-edge technology. Just as radar stealth and drones were game changers in the past, the acquisition process itself could become a game-changing technology in the future.

The Department of Defense (DoD) acquisition process transforms warfighter needs into materiel by three separate, but interlinked processes: the Joint Capabilities Integration and Development System; the Planning, Programming, Budgeting and Execution System; and the Defense Acquisition System. According to Chyma (2010), these processes answer four basic questions:

- What is the requirement?
- What is the acquisition strategy?
- What is the cost estimate?
- Is it affordable?

The current process is linear and document-centric, which makes the process of answering these questions in an integrated manner very challenging. According to Boehm (2010), “The weakest link in systems engineering is often the link between what the warfighters need and what the development team thinks they need, together with a shared understanding of the operational environment and associated constraints and dependencies” (p. 20).

FIGURE 1. GROUND SYSTEMS MUST BE ADAPTABLE TO A WIDE VARIETY OF OPERATIONAL ENVIRONMENTS



Note. TCO = Transnational Criminal Organization.

Systems Engineering 2025 (SE/2025), as described in this article, explores a possible future process to address shortfalls in the interlinked acquisition processes by using virtual worlds to enable new levels of collaboration and experimentation with changeable tailored platforms. The year 2025 represents a symbolic point in time where rapid manufacturing will start to provide the ability to produce systems effectively. The authors' intent is to outline how ground systems might be developed in 2025 as well as to describe current efforts underway to shape the future.

Figure 2 shows the SE/2025 process flow. The entry point into the process starts with the Persistent Synthetic Gaming Environments (left center) where thousands of soldiers may "kick the tires" on technologies and customize vehicles. This game-based environment will also provide a discussion group where soldiers can pool their collective expertise and brainstorm solutions. Meanwhile, engineers can observe what is working and program managers can assess the true tactical value of technologies versus cost. Real-time scenarios can be created for experimentation

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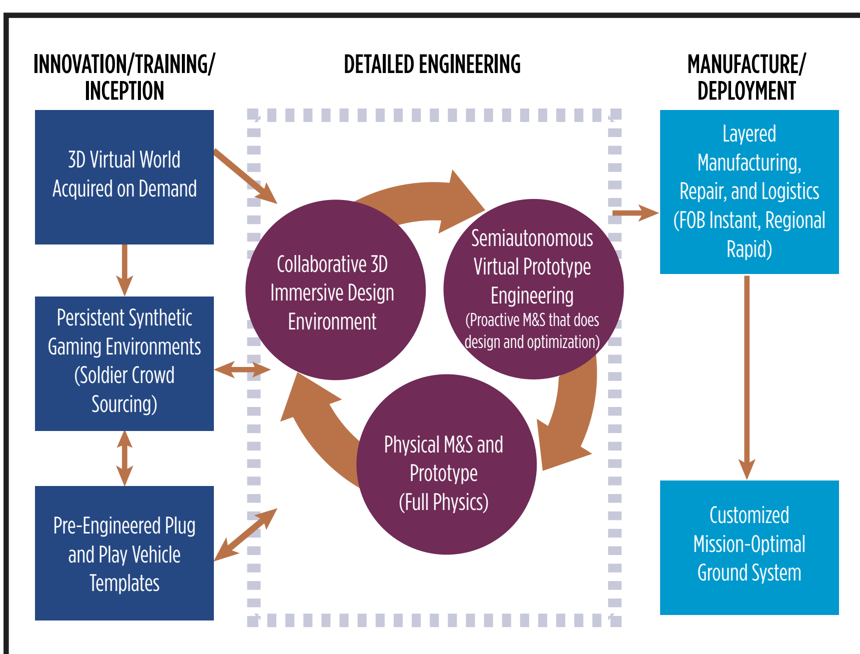
FIGURE 2. GROUND SYSTEMS SE/2025 "SYSTEMS ENGINEERING" PROCESS



Note. FOB = Forward Operating Base; M&S = Modeling and Simulation.

by using intelligence assets to create instantaneous geo-specific environments as shown in the upper left of Figure 2. To avoid overwhelming users with choices from the infinite combination of vehicle technologies, vehicle templates and capability modules will be evolved within the gaming environments as shown at the lower left of Figure 2. Vehicle templates are preferred configurations of modules and technology that the crowd of soldier-gamers proves to be robust for mission effectiveness. The templates will adapt over time as users share among themselves and piggyback on the best ideas. The overarching theme is that a tailored system will nearly always outperform a standardized system that tries to do everything.

While not explicitly illustrated in Figure 2, a critical feature for the success of SE/2025 is enhanced communication between stakeholders across the acquisition community. Korfiatis and Cloutier (2013) showed the promise of immersive environments (especially gaming environments) to facilitate a deeper understanding of CONOPs (Concept of Operations) by immersing the team in an experiential, first-person environment. To further maximize communications effectiveness, information should be provided at just the right time in a format or dashboard that allows quick interpretation of complex data and that hides irrelevant details. A recent emergence is the employment of tradespace exploration tools by both the Army Whole System Trades Analysis Tool (WSTAT) (Edwards, 2012) and the Marine Corps Framework for Assessment of Cost and Technology (FACT) (Browne, Ender, Yates, & O'Neal, 2012). FACT and WSTAT are both excellent examples of how SE is beginning to provide dashboard information to decision makers. These tools allow highly visual and interactive explorations of the tradespace, which would otherwise be extremely challenging to achieve. Employing modular designs will also help communications because modules are essentially black boxes that will only need to be dealt with at their interfaces.

The final section of SE/2025 in Figure 2 is Manufacture and Deployment. Manufacturing and Logistics will likely become inseparable in the future as localized production and rapid manufacturing have the potential to become the norm. The Army will find itself with new choices as to what is produced stateside, regionally, and at forward operating bases (FOB). True capability-on-demand will be realizable when rapid manufacturing, and plug-and-play modular components enable mass customization. Already, the Henry Ford-era mass production paradigm is eroding within the automotive industry where high levels of customization are increasingly available in the marketplace (Muller, 2010; White, 2012).

Deciding what is produced stateside, regionally, and at FOBs will depend on the portability of manufacturing equipment, nature of modularity, and deployment timeframes. Items that require large amounts of energy, materials, and specialized environments (like clean rooms) will likely be produced stateside. In contrast, some vehicle components might be digitally e-mailed to an FOB and produced expeditionary on site. A large benefit of 3D printing, also known as additive manufacturing, is that it takes a generic base material such as a powdered metal and fuses it layer by layer into a final piece. This means one machine and one base material can produce a quite varied set of components. The need to be rapidly deployable will drive designs toward kittable solutions to minimize the initial-entry airlift weight. Armor kits, for example, can then be applied later. Soldiers may swap modules on and off vehicles in the field—just like assembling Lego toys—to provide a rapid observe, orient, decide, and act loop (Boyd, 1996).

DoD SE Process Versus the Competition

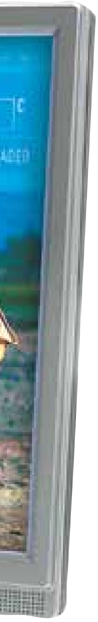
Presently, we are competing against the business models of terrorists and insurgents, and many countries threatening our nation's safety and security, which are "very much agile and open approach. They do not have thick internal R&D [research and development] establishments, and are willing to take knowledge and technologies from anywhere to achieve their goals" (Hood, 2007). Additionally, insurgents have made excellent use of the Internet for collaboration and knowledge sharing. They engage in rapid development and agile systems engineering through real-world application. Army General James Cartwright, former vice chairman of the Joint Chiefs of Staff, as quoted by Kitfield (2013), states, "… if you take the hunt for IED [improvised explosive device] cells, that was a 30-day fight." The enemy would invent a fuse, U.S. forces would develop a counter to it, and the enemy would respond by inventing another triggering device. "And if it took you longer than 30 days to respond to a change in enemy tactics,

your people were dying." The United States Army needs to shorten its materiel acquisition observe, orient, decide, and act loop (Boyd, 1996) to keep a decisive advantage over an innovative asymmetric enemy.

The current DoD process is a linear, requirements-first system in the translation of user needs into materiel solutions (Boehm, 2010). Due to the length of the existing process, decisions made and available technologies that were relevant at the beginning of a program may be obsolete by the end of the program. To quote the Chinese-authored Unrestricted Warfare, which discusses how developing countries might counter the United States, "Customizing weapons systems to tactics which are still being explored and studied is like preparing food for a great banquet without knowing who is coming, where the slightest error can lead one far astray" (Liang & Xiangsui, 1999).

Liang & Xiangsui (1999) further explore the fact that the United States generates a vast amount of technology on which it has been unable to capitalize, pointing out that:

> ...proposing a new concept of weapons does not require relying on the springboard of new technology, it just demands lucid and incisive thinking. However, this is not a strong point of the Americans, who are slaves to technology in their thinking. The Americans invariably halt their thinking at the boundary where technology has not yet reached. (p. 24)



Development of the first crowdsourced military vehicle, the Flypmode, by the Defense Advanced Research Projects Agency (DARPA) and Local Motors gives a glimpse of the potential for SE/2025. Jay Rogers, founder of Local Motors, points out conflicts are won not by spending tons of time and billions of dollars, but "They win it because they figured out what was going to beat the enemy, and they built that" (Boyle, 2011). Rogers went on to say:

> Maybe we did not do the same development that [the contractor] did, to make sure the strut on the vehicle lasts a million miles. But if it saves a life, and it lasts for a whole conflict, haven't we done a better thing? (para. 7)

President Barack Obama was shown the Flypmode vehicle, which only took 4 months to produce (Boyle, 2011), and enthusiastically pointed out:

> Not only could this change the way the government uses your tax dollars—think about it, instead of having a 10-year lead time to develop a piece of equipment, if we were able to collapse the pace of which that manufacturing takes place, that would save taxpayers billions of dollars—but it also could get technology out to the theater faster, which could save lives. (para. 12)

Persistent Synthetic Gaming Environments (Soldier Crowdsourcing)

The use of video games is not new to the Army. In 1981, General Donn A. Starry, then-commander of the U.S. Army Training and Doctrine Command, was struck by what he saw in the video game arcades (Trachtman, 1981):

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> I see a lot of people in those arcades learning something, and they're all volunteers, and they're paying a quarter to learn whatever it is they learn from these machines. I don't know what they learn, but I'm convinced they learn something, and that the Army needs to exploit it. (p. 56)

SE/2025 proposes to tap into thousands of soldiers, who already play video games in their spare time.

The Army Capabilities Integration Center (ARCIC) has begun an experiment called Early Synthetic Prototyping to create a persistent gaming environment to answer the following question:

> How does the Army develop and implement a process and a set of tools that enables soldiers to assess emerging technologies in a synthetic environment to provide relevant feedback that informs science and technology research, doctrine, organization, and training development?

Past game-based experiments were not persistent and were limited in participation to a relatively small user base. The target of the ARCIC investigation is to involve upwards of a thousand soldiers in the gaming, which is crowdsourcing. However, open research questions remain unanswered about this methodology, including:

- Can we draw (explicitly and/or implicitly) useful feedback from soldiers about future technology capabilities using a game environment as a concrete experience?
- Are the results of analysis from soldier feedback significantly different from the results of analysis from traditional experimentation?
- How do we begin to allow soldiers an active role in the design of platforms?

Research is presently being conducted by the authors to answer these questions.

The fundamental purpose of creating a persistent gaming environment for SE is to generate a sandbox for testing out new tactics in conjunction with science and technology (S&T) simultaneously. Dr. Peter Singer, director of the Brookings Institution 21st Century Defense Initiative (Unmanned Systems, 2010), observes that "knowing that having the right doctrine can be the difference between winning and losing wars, between committing America to the 21st century version of the Maginot Line vs. the Blitzkrieg." SE/2025 has the goal of generating 21st century blitzkrieg by directly allowing soldiers to experiment with doctrine directly. Soldiers can then feed experiential insights and measurable data back to engineers and decision makers. Conversely, the art

of the possible for cost, timing, and technology can be provided back to the soldiers. The speed of feedback produced in a gaming environment suggests the potential for engineers, program offices, and soldiers to codevelop systems. Gaming environments might even allow an assessment of the battlefield value of S&T investments prior to committing research dollars to actually develop the technology. The final benefit of using synthetic environments is that soldiers will more readily adopt new equipment if they have already used it in a virtual environment. It is not uncommon for new equipment to sit at the FOB because soldiers simply are not comfortable and familiar with it.

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To develop robust templates of the most effective vehicle configurations, many iterations of the same scenarios should be performed due to the stochastic nature of decisions made during a battle (Weber, 2012). A slight deviation in timing or difference in course-of-action could vary the battle outcome greatly so stochastics are important. Another critical element to maximize the benefit of these environments is to provide a discussion forum for users to exchange tips and tricks, and to learn by replaying winning and losing scenarios. Collaboration among players will ensure maximum leapfrogging of ideas—known as crowd accelerated innovation (Anderson, 2010).

Figure 3 shows how a persistent gaming environment will engage the Army DOTMLPF-P (Doctrine, Organization, Training, materiel, Leadership and Education, Personnel, Facilities–Policy) communities. The environment should have several specific features: First, it should provide a sandbox where soldiers may build and modify ground systems (and scenarios) as they see fit. Second, the physics fidelity should be modifiable to allow engineers to tailor the game with applicable real-world physics as appropriate. Third, it should be template- or module-centric to avoid overwhelming users with too many combinations and choices so they can only focus on relevant details. Fourth, there must be a discussion and sharing area that allows replays and piggybacking on ideas.

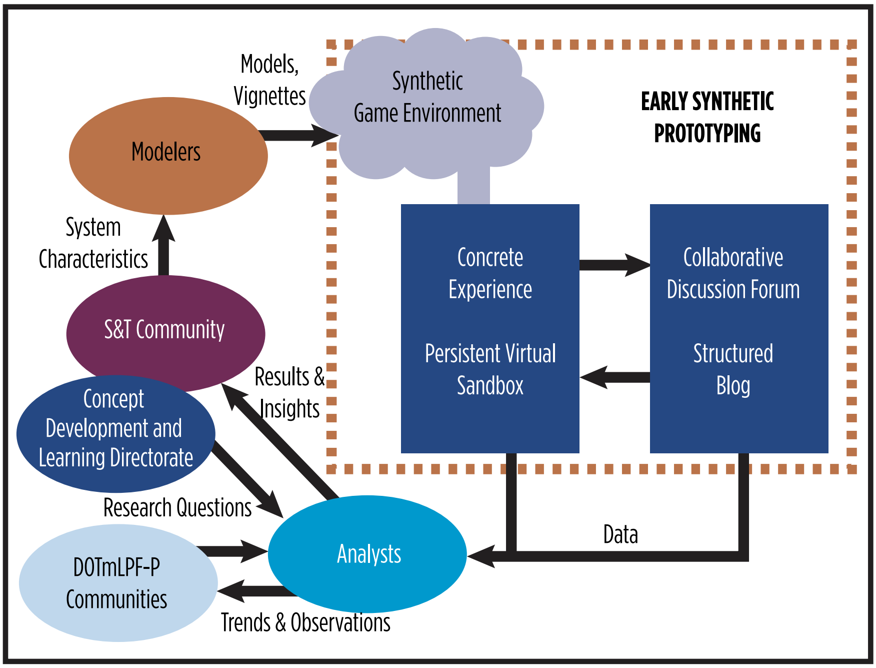
3D Virtual World Acquired on Demand

The spectrum of future operations covers a variety of known and unknown threats, and variable reaction timelines. It is now possible to capture, in real-time, a battle scenario that may be input into a gaming environment or passed on to engineers for the development of mission-specific ground systems. Planners for the raid on Osama bin Laden's Abbottabad, Pakistan Compound used satellite imagery from the

National Geospatial-Intelligence Agency to create models of the compound prior to the actual attack. The models were used to allow the Joint Special Operations Command to create mission simulators for the pilots who flew the helicopters to practice virtually ahead of time (Ambinder, 2011; Harris, 2011). This rapid construction of 3D scenarios will continue to evolve and blur the line between simulations and reality.

Either satellite imagery or air-/ground-collected imagery may be used instantly to construct realistic scenes. Depending on the application, various sensor modalities may be employed. DARPA and Space and Naval Warfare Systems Command (SPAWAR) have both made progress on a number of projects that help to make instant scenarios available. The DARPA RealWorld Project (Intific, n.d.) has a goal of creating high-definition scenes in under 30 minutes. SPAWAR's UrbEM Project (Nguyen et al., 2009) aims to develop, mature, and demonstrate technologies that will provide rich 3D models of complex urban environments from the ground perspective, mainly using sensors normally found on unmanned ground vehicles. UrbEM has investigated the following technologies that may be used to develop scenarios: structure-from-motion, multiview

FIGURE 3. CONCEPT OF THE PERSISTENT GAMING ENVIRONMENT



stereo, laser scanning fused with color image data, spatial phase video, and registration software/algorithms. An example of an UrbEM experiment is shown in Figure 4 where multiple views are automatically combined to create a 3D model. Similar effects may be achieved where video frames are continuously acquired. The Microsoft Photosynth project (Photosynth, n.d.) demonstrated the ability to create 3D geometry from a collection of online pictures, which is stunning considering it requires a computer to combine multiple views, lens, lighting, and even the inclusion of people in photographs. With Photosynth, it is possible simply to use Web-based photo repositories such as Google Images or Flickr to create 3D models of objects autonomously.

Preengineered Plug-and-Play Vehicle Templates

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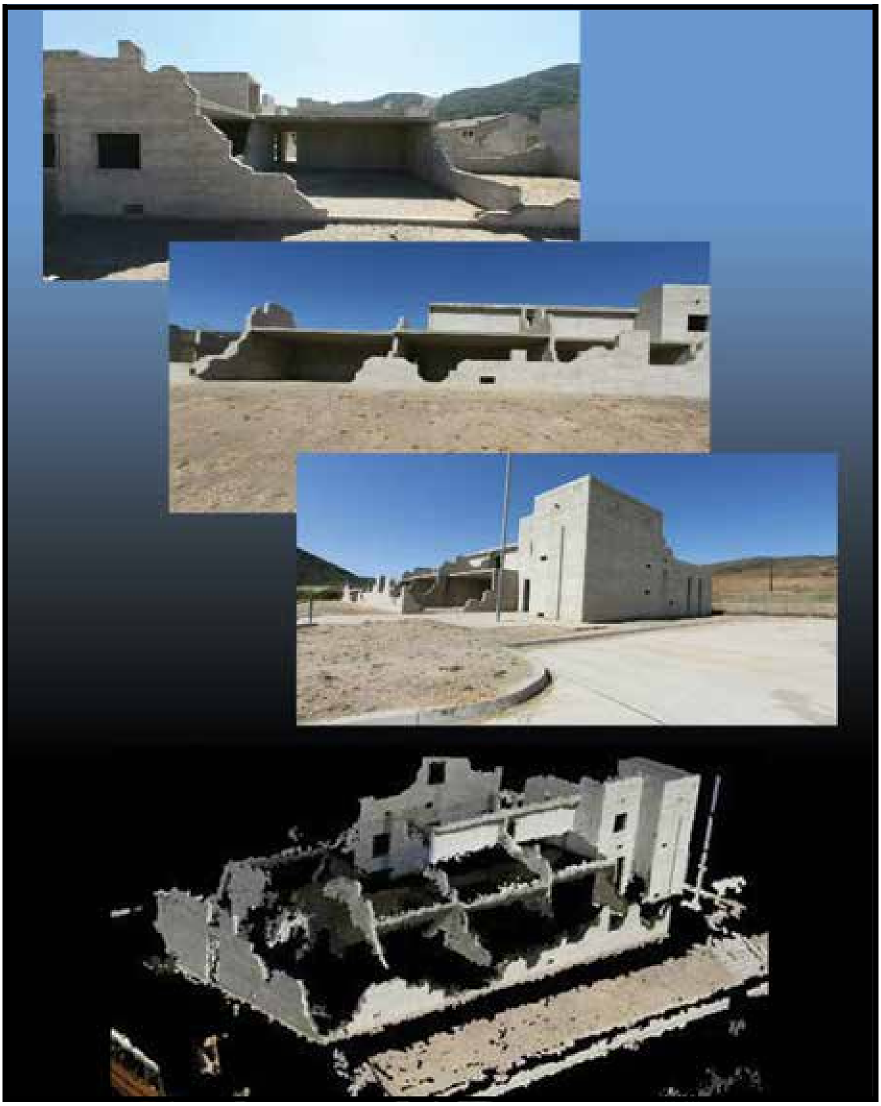
A template in the context of future vehicle design is an assembly of modules that is a doctrinal preference for a successful outcome. Templates are key to the rapid fielding of different solutions based on terrain, enemy, mission, or other considerations. Imagine a case where there will be a sustained operation requiring the capture of insurgents. Users should be able to select preengineered vehicle templates to try out in advance to see what works best. Once they find that a robot or tank works well, they can tailor the template vehicle to their tastes and preferences. Having a generic starting template is important in case an event occurs that requires an immediate response, allowing no time to customize vehicles beyond what is captured already in the template. This is also important for experimenting in the gaming environment so players have base vehicles with which to play in the virtual environment without starting from scratch. The development of templates encourages innovative evolution of designs within the gaming environment by allowing easy modifications. A distinct combat advantage is to be gained from tailoring because it will confound the enemy's ability to exploit a common vulnerability—the Achilles' heel might always change.

Templates, along with modularity, are critical to avoid decision paralysis in the face of too many options. Information overload directly reduces the human ability to make smart, creative, and successful decisions (Begley, 2011). As promising vehicle configurations evolve from the persistent gaming environment, these can be tied to classes-of-use cases for a vehicle that may be deployed. These configurations can then be progressively tailored as more information about a conflict becomes known or the greater the probability of a certain type of event occurs, as shown in Figure 5. Individual commanders will be able to customize the base templates as needed for specific missions—be it in the real world or virtual world. This evolving design methodology is supported by having

FIGURE 4. RECONSTRUCTIONS OF 3D MODELS: STRUCTURE AT CAMP PENDLETON MILITARY OPERATIONS ON URBAN TERRAIN COMPOUND



Note. Multiple images allow on-the-fly reconstructions from a series of photographs as part of the UrbEM project. Adapted from Nguyen et al. (2009).

discussion forums and replay capabilities for soldiers to discuss what options are most desirable and to share first-person virtual operational experiences with other stakeholders.

Detailed Engineering

Detailed engineering starts with Semiautonomous Virtual Prototype Engineering (Figure 2). Virtual Prototype denotes the fact that physics-based models have already become accurate and multidisciplinary enough that they should be considered digital (or virtual) prototypes. Semiautonomous implies that future modeling and simulation (M&S) will be more proactive than current computer aided design (CAD) since some design work can be done collaboratively with computers. Conventional M&S such as computational fluid dynamics, finite element analysis (FEA), and other computer aided engineering methods are traditionally reactive and simply provide an engineer with an assessment of performance; the engineer must manually fix the design and rerun the model. For example, consider the design of some structural part: Right now, an engineer creates a design in CAD, runs an FEA analysis and, based on the results, repetitively tweaks the design until the part functions as intended. In the future, the engineer will merely describe the use-case of the part (and constraints) to the computer and, using M&S, the computer will autonomously optimize the part. In 1982, Gunn estimated that "only 20% of the parts initially thought to require new designs actually need them; 40% could be built from an existing design; and 40% could be created by modifying an existing design" (Gunn, 1982). For this reason, a number of universities are already working on autonomous part search methodology (Iyer, Jayanti, Lou, Kalyanaraman, & Ramani, 2005).

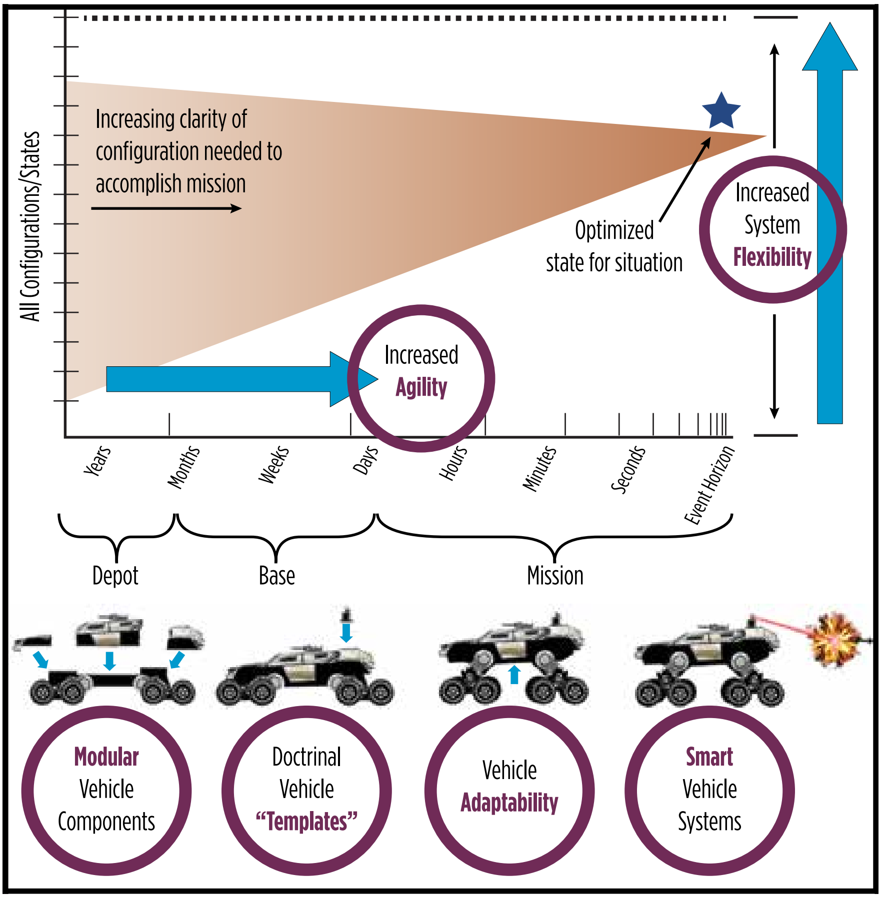
The future SE detailed engineering process will be based on pervasive prototyping. IDEO, designers of Apple's first mouse, the Gripper toothbrush for Oral-B, and the Palm V point out that "if a picture is worth a thousand words, a good prototype is worth a thousand pictures" (Kelley & Littman, 2001). Prototyping can be virtual (all within a computer), physical, or a combination of the two such as hardware-in-the-loop simulations. Decisions made during detailed design must be captured with ubiquitous knowledge management. Knowledge is expensive to generate and ignorance is even more expensive.

Physical prototyping supplements pure M&S (virtual prototyping) by validating assumptions and identifying unknown interactions. In particular, subsystem-level prototypes can be combined with modeling to enable hardware-in-the-loop simulations and man-in-the-loop simulations. The act of building something in itself is incredibly informative. Systems integration laboratories (SILs) also fall into the category and test the integrated function of multiple components. SILs are critical because SE fails most frequently at the interfaces. Examples of a physical simulation are shown in Figures 6 and 7.

Layered Manufacturing, Repair, and Logistics

The future force might be substantially redefined by new options presented via rapid manufacturing, and particularly additive manufacturing. Per Wikipedia (Rapid Manufacturing, n.d.), "Rapid manufacturing is a

FIGURE 5. TEMPLATES OF MODULAR VEHICLES AND PLAN FOR MANUFACTURING AND LOGISTICS



Note. Such templates and plans will become inseparably coupled in the future.

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technique for manufacturing solid objects by the sequential delivery of energy and/or material to specified points in space to produce that part." 3D printing reduces the number of separate machines necessary to create a part by transforming powdered or liquid raw materials layer by layer into a final piece. Additionally, additive manufacturing allows the elimination of welding, brackets, and flanges when the piece can be produced as a whole. Conventional machining processes remove material, which creates waste, where additive manufacturing only places material where needed. Finally, additive manufacturing may also be used to make repairs. General Electric has demonstrated an ability to repair worn parts by using a precision spray technique to add material to an existing part (General Electric, 2013).

A new ability to produce parts locally may substantially change procurement and repair logistics. Future logistics (notionally illustrated in Figure 8) must optimize the movement of materials and manufacturing equipment to provide maximum flexibility and minimal cost. Items that require large amounts of energy, materials, and specialized environments will likely be produced stateside. Some items may be manufactured at the FOB using technologies such as 3D printing. The Navy explored the notion of ships becoming floating factories in a Proceedings Article (Cheney-Peters & Hipple, 2013), possibly even harvesting resources from

FIGURE 6. U.S. ARMY TANK AUTOMOTIVE RESEARCH, DEVELOPMENT AND ENGINEERING CENTER (TARDEC)'S RIDE MOTION SIMULATOR (RMS)

Note. TARDEC's RMS is an example of a man-in-the-loop physical simulation.

the surrounding seas or ashore. Due to the intrinsic complexity of customized platforms, it will be critical to use information technology to form an effective manufacturing and logistics strategy.

Army Captain Elsmo (1999) provides a simplistic storyline. In reality, a ground system will probably have multiple components coming from a variety of locations. Assemblies and subassemblies may be created anywhere in the logistics and manufacturing chain. This gives a very new meaning to what the life cycle of a product and its constituent modules may become.

The layered manufacturing/logistics process is tied directly to the gaming environment and detailed engineering process. Figure 5 shows how modules and developed templates for ground systems evolve in lock step with manufacturing and logistics. As more information develops about the potential materiel need, more definition of the design is provided. Once a system has been fielded, modules allow a vehicle to be adapted by changing out these modules. Examples include kittable armor, swapping out radios, upgrading sensor packs, or retuning engine control modules. Further, the vehicle itself will be smart. An example of a smart vehicle is one that senses a cargo load and then automatically reprograms its stability control and antilock braking to accommodate the load.

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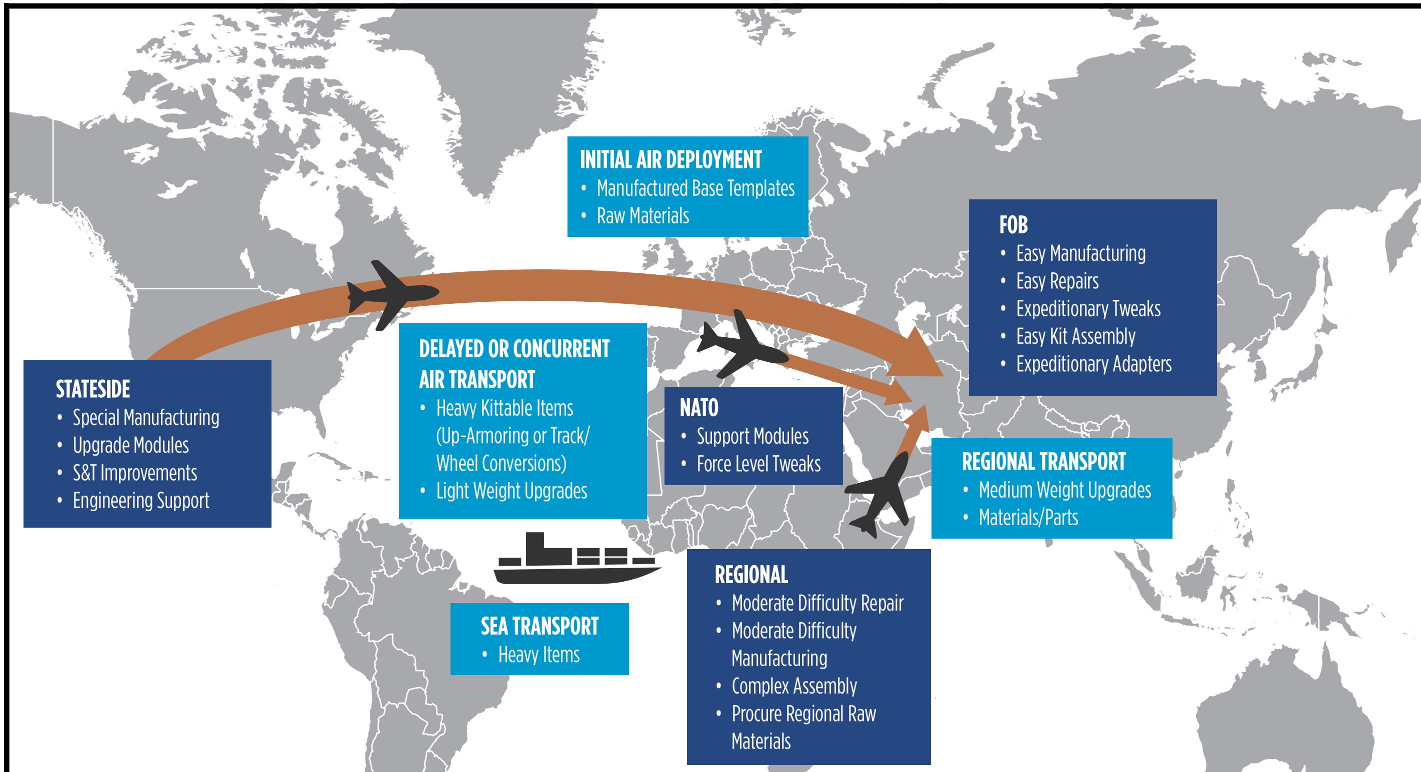
FIGURE 7. U.S. ARMY TARDEC'S N-POST SHAKER

Note. TARDEC's N-post shaker is a hardware-in-the-loop simulation.

FIGURE 8. NOTIONAL FUTURE LAYERED MANUFACTURING/REPAIR/LOGISTICS



Note. With the onset of Future Layered Manufacturing/Repair/Logistics, the movement of materials and manufacturing equipment is optimized to provide maximum flexibility and minimal cost.

The notion of local manufacturing is not entirely new to the Army. The U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC) had fielded a mobile parts hospital in the past, which was the automotive equivalent to the mobile army surgical hospital unit, providing treatment to a vehicle so its crew is protected and could finish the mission (Williams, 2004). The Rapid Equipping Force began fielding expeditionary lab mobile units in 2013, which include 3D printers, computer-assisted milling machines, and laser, plasma, and water cutters, along with common tools like saws and welding gear (Hill, 2013). The industry is fast approaching a point where even static structures such as buildings may be 3D printed (University of Southern California, n.d.). Logistics must also modernize to take advantage of these new production technologies. Boeing has already used 3D printing to make more than 22,000 parts used on civilian and military aircraft flying today (3d Printing Era, 2012).

Due to changes in manufacturing and logistics, the defense industry could start to shift away from the historical big contract methodology where large defense contractors are awarded a contract to develop an entire vehicle based on requirements documents that may exceed 300+ pages. In the world of commercial automotive, the lines have already started to blur as to what the brand name of a vehicle means. Engines come from one manufacturer, bodies another, and electronics another. Looking further into the future, the manufacture of a future ground vehicle may become a very layered manufacturing and logistics process. The role for contractors in such a future may be to develop modules and subsystems that plug-and-play with vehicles. Additionally, contractors might supply manufacturing equipment and maintain the logistics base that will enable mass customization. Such a shift would have an impact on the planning and budgeting process, which is focused on platforms in contrast to modules.

Conclusions

The complex nature of future global conditions requires ground vehicles that are adaptable, flexible, smart, and rapidly deployable. The very nature of this type of vehicle requires an agile SE process that anticipates many scenarios in advance. Using persistent synthetic gaming environments may help develop vehicle templates that consider tactics and technology concurrently. Templates will provide the most robust mission (and cost) effectiveness while still allowing for tailoring. Rapid manufacturing and nonstatic mission requirements are quickly making one-size-fits-all military ground vehicles an obsolete concept. Logistics may be transformed into a deeply interlinked manufacturing/repair/logistics process with localized production and assembly of many parts or modules. Readers should consider whether the next great technology breakthrough for the Army might be an agile systems engineering process that is infused with crowdsourced soldier input, concise communication of information, and proactive M&S tools.

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