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The Digital Battlefield: A Behind-the-Scenes Look from a Systems Perspective

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Abstract

The last decade and a half has seen major advances in computing, communication, and display technologies. The U.S. Army has been proactive in harnessing and combining these technologies under a common rubric called the "digital battlefield." The digital battlefield, which has become the primary mechanism for real-time situation awareness, has become a force multiplier that has transformed the Army to meet and overcome the challenges of the 21st century. Today, all elements of a U.S. Army combat team – tanks, fighting vehicles, helicopters, artillery, and convoy / support vehicles – are interconnected within the digital battlefield. The result has been a dramatic improvement in combat power, accompanied by a marked decrease in U.S. force casualties. This paper takes a behind the scenes look at the science and technology that led to this signature transformation of the U.S. Army combat forces. The paper discusses critical success factors and lessons learned. The paper concludes with a brief discussion of civilian sector benefits of FBCB2 technology and subsequent variants created by DoD.

Keywords:situation awareness, digital battlefield, context-aware computing, systems approaches, systems thinking, command and control

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1. Introduction

The last decade and a half has seen major advances in computing, communication, and display technologies. The U.S. Army has been proactive in harnessing and combining these technologies under a common rubric called the "digital battlefield." The digital battlefield, which has become the primary means for real-time situation awareness to the U.S. Army[1,2,3,4,5], has become a force multiplier that has transformed the Army to meet and overcome the challenges of the 21st century. Today, all elements of a U.S. Army combat team – tanks, fighting vehicles, helicopters, artillery, and convoy / support vehicles – are interconnected within the digital battlefield. The result has been a dramatic improvement in combat power, accompanied by a marked decrease in U.S. force casualties. This paper takes a behind the scenes look at the science and technology that led to this signature transformation of the U.S. Army combat forces.

The system called "Force XXI Battle Command Brigade-and-Below" (usually, and hereafter, "FBCB2") is the U.S. Army's principal combat battle command system. It provides command-and-control, situational awareness, logistics management, and other key functionalities to front-line combat forces in all branches (armor, artillery, aviation, infantry, intelligence, combat service support, air defense, etc.) of the U.S. Army. In early 2003, this system was also adopted by the U.S Marine Corps. This system is also referred to as the "Blue-Force Tracking System," or the "Blue-Force Tracker."

Today, FBCB2 is the centerpiece of the Army's effort to "digitize the battlefield." Battlefield digitization means the achievement of a significant increase in land combat force effectiveness through the introduction of information technology in every type and class of U.S. combat platform on the battlefield. Considered to be a highly-successful program[6], it is credited with significantly increasing U.S. Army combat effectiveness[7], while saving the lives of U.S. and U.K. forces in the Balkans, Iraq, and Afghanistan[8]. In light of these successes, it has been designated by the U.S. Army and the U.S. Marine Corps as the basis for their tactical battle-command automation improvement plans for the next 20 years[9]. About 100,000 units of this system have been successfully deployed to date.

An early version of the FBCB2 computer mounted at the commander's position in a M2A3 Bradley Infantry Fighting Vehicle is shown in Figure 1. In some variants of the Bradley, there is also an FBCB2 computer mounted in the squad area in the back of the vehicle. The installation of this system has demanding human-factors, safety, size, power, and heat dissipation requirements. FBCB2 is similarly integrated into most of the 50 or so types of vehicles operated at the tactical echelons by the U.S. Army and U.S. Marine Corps.

Fig. 1. FBCB2 in a combat platform

Figure 2 depicts an actual screen image from an FBCB2 display captured during an unclassified test in 1998. It provides a moving real-time "situational awareness" display†. The screen, about 11" diagonally, is generally

† Interestingly, after extensive testing of various alternatives with users, it was decided to operate the system with north as the top of the screen, rather than have the map rotate to the cardinal points (a capability that exists in the software). The ability of the screen to rotate automatically to the cardinal points is a key and valued feature of the FAAD C^2I gunner's terminal from which this device was derived. However, the same

operated via touch (with the fingers, or with a stylus – fingers don't work well with arctic mittens or chemical-protection gloves). The "touch areas" at the right are quite large to ensure effective use in a moving, continuously-vibrating vehicle. The intent was to allow complex messages (e.g., call-for-fire) to be composed on-the-move in less than 10 seconds.

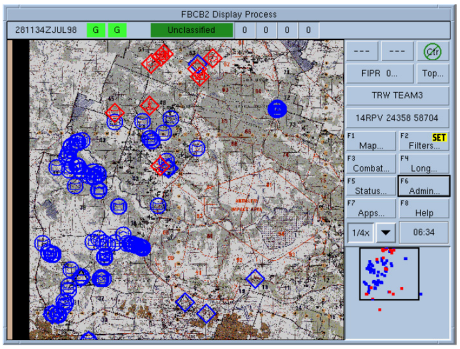

Fig. 2. FBCB2 display image

FBCB2 has had a profound impact on U.S. and allied ground combat teams. Large-scale force-on-force exercises, and analysis by the U.S. Army Training and Doctrine Command (TRADOC), have demonstrated more than a two-fold improvement in overall force effectiveness. In August 1998, free-play force-on-force exercises at Ft. Hood, Texas, resulted in outcomes that showed three-fold and four-fold improvement in force effectiveness. The technology has also proved itself through its use on tens of thousands of vehicles in actual combat operations (in Iraq and Afghanistan), and in peace-keeping operations (in Bosnia and Kosovo), resulting in many lives saved with improved combat operations. The system received numerous commander citations stating that "Blue Force Tracking" was one of the most decisive new military technologies of our times[10].

FBCB2 development was motivated by the desire to "lift the fog of war". Prior to FBCB2, the ability of a combat team to coordinate operations was limited; dust, smoke, line-of-sight limitations on radio communications, jamming of radio signals, and overall confusion generally prevented all but the most rudimentary coordination of activities, and usually posed an obstacle to any significant adaptation to rapidly-changing conditions.

The Army adopted the term "situational awareness" to describe the desired state for any team member: everyone on the team was to know "where am I," "where are my friends," "where is the enemy," and "what are their capabilities." The team members would have accurate and timely information about geographically-fixed entities, such as the location and status of mine fields and contaminated areas. The team members could send and receive digital and graphical orders, issue and react to calls-for-fire and calls-for-support, and other related capabilities. The key hypothesis – confirmed by simulation, large-scale field experimentation, and actual combat operations – is that situational awareness allows friendly forces to operate more effectively and consistently than previously possible, and well within the adversary's decision cycle[11].

To achieve this capability, a number of conceptual, scientific, and technological advances were needed. This paper discusses some of the key challenges, and the methodology developed and employed to overcome these challenges and achieve desired outcomes. The paper also describes ongoing work in this vitally important area.

2. The Digital Battlefield and Its Challenges

Before the Digital Battlefield effort got underway, the U.S. Army already had an established methodology for conducting combat operations. Consequently, the work on the Digital Battlefield began as a "process re-engineering" effort that envisioned new concepts and devised new approaches for combat operations, and then

capability was deemed to be a distraction in this application.

identified those alternatives that provided the greatest benefits while also satisfying legal and social constraints of combat. A new set of "mission threads" (i.e., action sequences that underpin the "process" of tactical war fighting) was created and validated for combat operations[‡]. The initial set of mission threads focused on heavy force operations – large-scale armor and mechanized infantry forces, supported by aviation, artillery, and air defense. These reflected a core set of Army missions, and were also among the most demanding in terms of their need for constant mobility in the face of a lethal enemy threat. Later, concepts of operation (CONOPS) for smaller-scale deployments (e.g., peace-keeping in the Balkans, small dispersed combat teams in Afghanistan) were added. Network-enabled situational awareness became a popular phrase to describe this new "process."

In this process, the key mission threads at the *system* level involve a variety of interactions on the part of the commander of the FBCB2-equipped unit with higher military authority (responsible for establishing operational orders for the unit), coordination with peer FBCB2 systems (operating in support of nearby tactical units, such as an adjacent brigade combat team), interactions with other battlefield automation systems (e.g., systems that perform specialized functions such as artillery ballistic calculations), assorted battlefield sensors, and personnel operating FBCB2 systems (in tanks, jeeps, helicopters, and fighting vehicles). Other interactions include those with the world-wide FBCB2 management structure (implemented in a network operations center), and the enemy who can potentially be observed, reported on, and engaged in military action.

Mission threads also exist at the individual *node* level. One such thread involves developing local information for sharing with the combat team (e.g., own position, own status, locally-obtained knowledge of the enemy such as data on enemy position derived from a laser-range finder, locally-developed assessment of enemy intentions, locally-developed information regarding geographic entities such as reports of bridges that are damaged, contaminated areas, minefields), and then applying appropriate algorithms rules for frequency of data sharing to manage network load. Another thread involves acquiring information from the network and turning it into a locally-tailorable "common operational picture." In this regard, all displays in the same vicinity have the same information available; however, each vehicle commander can tailor how the data are organized and displayed to suit their needs and command style ("user-defined operational picture"). Default tailoring of these settings is provided, based on the role of a particular vehicle within the combat team ("role-based processing"). This strategy minimizes the workload of those who are engaged in combat operations, and who have little time to tailor the system[12,13,14]. A further set of threads involve requests from FBCB2-equipped platforms for off-platform resources, such as call-for-fire, call-for-support, and requests for re-supply. Some of these requests are generated automatically by the system, while others are generated by the operator. Additional threads interact with weapons and other on-board systems, including specialized sensors.

Once new combat processes were formulated, the question of how best to implement the new process (i.e., equipment, training, personnel) had to be addressed. Not surprisingly, several challenges surfaced during assessment of ways to implement the digital battlefield:

- **Capability implementation across the entire land combat team.** This would eventually comprise hundreds of thousands of vehicles. The unit cost per vehicle, therefore, became a major design consideration.
- **Connectivity on the move.** Since combat is conducted on the move, the network that provided data (and voice) connectivity had also to operate on the move[1], and to operate through a variety of "harsh" conditions (e.g., foliage, line-of-sight obstructions, jamming and other sorts of electronic interference, constant changes in the composition and organization of the combat team).
- **Manageable cognitive load.** The demands on human operators of the system had to be realistic, given combat stresses, distractions, additional assigned tasks, and skill levels of users. [1,12,13,14,15]
- **Trust, reliability, and accuracy.** Both reliability and accuracy are paramount, given the life-critical nature of the missions. The system was to be used when making decisions regarding the application of lethal force, and therefore had to be trusted to be accurate, timely, and correct.
- **Resilient combat operations.** Combat operations are typically conducted over a wide range of environmental conditions (e.g., temperatures and varying weather conditions); as such, combat equipment is

[‡] The Army uses the terms "concepts of operations", or CONOPS.

subjected to a variety of off-nominal environmental stressors such as high levels of vibration, shock, and moisture.[16,17]

3. Affordable Systems Approaches

Various affordability-driven systems approaches that exploited knowledge of context and domain were used to overcome these challenges. These are discussed next:

- **Context-aware networking**[1,11] – how to deliver data reliably and in timely fashion (for operational effectiveness) to members of the combat team, on-the-move in complex terrain, and in hostile electronic environments. This was the core challenge; combat can seldom depend on civilian communications infrastructure (such as the cell phone network); cell phone towers are easy targets, combat operations often take place in locations far from cell infrastructure, and it is important to be able to control the electronic signature of the combat team. Specific advances achieved by FBCB2 include:[18]

    - ***Force-structure-aware network***. A continuously updated communications network with deep knowledge of the military force structure that it is supporting, and the innovative network management mechanism that enables it, are the basis for achieving reliable wireless communications interconnectivity of thousands of mobile platforms with low-cost (and unreliable) radios, and most importantly, without any pre-existing infrastructure elements (e.g., no cell towers, fixed-site relays). In this context, routing decisions could be optimized because the network is aware of both the users and the mission applications. Cognitive load on users is thereby reduced, because the network determines the mapping from combat-team roles (e.g., executive officer of the 2nd battalion, 1st brigade) to IP addresses. This mapping was complex and dynamic, and new sorts of decision-support algorithms had to be created in order to automate this process with high credibility.

    - ***Adaptive communication protocols***, including unicast routing that determines the route at the time of the service request (rather than based on cached data, which is how the Internet works); reliable multicast that works over low-bandwidth communications; quality-of-service provision over communications bearers not designed to provide quality of service (QoS); and Internet Protocol (IP) header compression mechanisms, which ride on top of standard IP mechanisms, and interoperate with commercial protocols (e.g., TCP, OSPF, BGP-4, etc.) at the edge of the mobile network.

- **Human capabilities-aware function allocation and human-systems integration** – Human-machine function allocation is a key aspect of maximizing joint human-machine performance while assuring that tasks assigned to humans do not exceed human cognitive limitations.[19, 20, 21] Also, it was imperative that soldiers were not tasked to monitor and operate computers in tanks on a full-time basis. This is because humans are ill-suited to monitoring infrequent events or perform multiple concurrent activities.[20,21] Humans are also poor at multi-tasking and context-switching, even though circumstances can arise when multi-tasking is unavoidable.[20,21] The key challenge was determining how best to design the information and the operations of the system so as to add value within the capabilities, time constraints, cognitive limitations, and acceptable stress-levels of the users.

- **Affordable operations in combat environment** – DoD has been building complex electronics capable of operating in demanding physical environments (e.g., vibration, shock, heat, cold, glare) of a combat vehicle for quite some time, but at unaffordable prices.[16] To field this capability at an affordable price in 250,000 vehicles required a 6X price reduction per unit, compared to the status quo; in fact, a better than 10X reduction was achieved. This advance was enabled by novel technology-driven methods that enabled operations in the presence of vibration, shock, and heat, and a strategy called "modernization through spares." The latter enabled the use of carefully-selected commercial electronics parts, while circumventing the need to maintain an inventory of obsolete parts for years.

- **Software dependability and reliability** – There was an expectation that once established, the network would be available 100% of the time, surviving individual vehicle failures, and continuing to operate as the force moved, reconfigured, and reconstituted itself at rates well beyond the rate of change of commercial communications and computer networks. In response to this challenge, the Digital Battlefield project created new techniques for controlling complex networks, and adapting the configuration dynamically in response to the needs of the combat force, with relatively modest actions required on the part of the operators. Also, the large amount of onboard software needed to be ultra-reliable. To accomplish this, innovative techniques were employed to partition large software developments into manageable work packages which matched the assigned work to the talent available within real world teams. Also, techniques were created for software integration risk reduction through design strategies that separated functional modules from elements controlling dynamic software behavior. Successful realization of this capability significantly improved the reliability of large-scale software applications, while also improving the predictability of software deliveries.[10]

Specific engineering trade-offs were conducted to address the aforementioned issues, and to do so within a schedule-first priority scheme. The Army believed that it had achieved a level of organizational consensus to "test-drive" the digital battlefield concept, and wanted to reach a level of success before the consensus dissipated and/or w distracting events scuttled plans. The Army's goal was to get through the experimental phase, development, and reach the milestone of first-unit-equipped (e.g., the initial formal fielding to an operational unit) in about four years. This duration is around one-third of the time it typically takes for a complex weapon system to proceed from initiation to first-unit-equipped. Once the project got underway, risks were identified, and multiple approaches were funded and carried through to development for an unusually long time (for example, three versions of the vehicle-mounted computer participated in the initial experiment). Non-core capabilities were deferred to maintain schedule for the core situational awareness capability. It was recognized that, in the event of total success (and therefore, fielding the system for the entire Army) that the majority of the costs would be incurred after development was complete, e.g., during production, operations and support, and the costs were managed accordingly. As a result, development effort was spent both on (a) reducing the anticipated production costs of the core mission equipment (especially the vehicle-mounted computer), and (b) reducing the anticipated operations costs, primarily by creating a modernization-through-spares strategy, wherein the system was designed so that old failed parts (e.g., disk drives) could be replaced with newer parts. Old parts would not have to be stockpiled for years; improved capacity could be provided through the use of newer parts. To accomplish this, design had to isolate the impact of such parts changes from the typical "ripple" across the system, e.g., avoiding the new for significant re-testing of electromagnetic compatibility, of temperature compatibility, avoiding the need to re-certify air-worthiness and safety, and so forth. Many stakeholders across the Army were involved when approving a design that met these criteria.

4. Methodological Perspective

The U.S. Army had an established methodology for developing combat systems. To incorporate the foregoing S&T advances while simultaneously transforming the methodology, a formal system development and evaluation framework was created to guide FBCB2 development and data collection.

The overall methodology was informed and motivated by the U.S. Army's hypothesis: "The use of digital information, down to the lowest echelons of the combat team, would improve combat effectiveness." Thereafter, a formal experimental methodology was established that employed digital force-on-force exercises (termed "Army warfighting experiments"), at various sizes and echelons, employing actual combat units, and extensive controls and instrumentation.[22] Pursuant to that, a measurement and instrumentation framework for data collection and analyses was established.

The Army designated an active-duty combat unit (the 4th Infantry Division) as the Army's "Experimental Force" (the unit retained its role as a warfighting force; the division participated in combat missions during this time). The division command was incentivized to conduct the experimentation. Specifically, their efficiency ratings and promotions were determined, in part, by how well their units supported the experimentation process (they were ***not*** rated on the outcome of the experiments). Highlights of the development approach are discussed next:

- **An incremental, spiral development model**[23] was adopted. A key innovation was that each major release was sent to actual warfighting units for assessment; in addition, in a surprising departure from policy, the contractor-led development team was given unprecedented access to warfighters to extract and document lessons-learned.[24]
- **Changes suggested by warfighters were addressed** (to the extent possible) in the very next increment / spiral of capability. Warfighters were encouraged by the fact that their feedback was influencing the development process.
- **Options were carried as late as feasible** to maximize flexibility. The design / implementation trade-space management strategy allowed alternatives to be carried for as long as possible into the development cycle.[16] This strategy was essential due to the high risk associated with multiple concurrent scientific findings / technological advances being introduced simultaneously during development.
- **A continuous development, assessment, and adjustment cycle was implemented** in the new warfighting process and mission threads.
- **A parallel spiral model was implemented** to determine the military worth of each new technology while mitigating risks. Test and evaluation was both difficult and laden with risk because the program started without agreement among the stakeholders of how the operational value of the new capability could / should be measured. This parallel process allowed developers and operational assessors to reach agreement on the appropriate metrics for measuring operational value, both in technical terms, e.g., "SA visibility", and in operational terms, e.g., "loss-exchange ratio." Furthermore, it was agreed to share test instrumentation across both developers and operational assessors. Thereafter, multiple independent teams, designed, built, and utilized their own tools to analyze their respective data. This strategy ensured independence of analysis, while also affording the opportunity for teams to critique and learn from each other.

5. Conclusions and Outlook for the Future

5.1. Evaluation Results

The FBCB2 was validated through a series of Army Warfighting Experiments (AWE) held in the 1996 through 1998 time-frame. The results were considered convincing, as evidenced by the following quote from an Army assessment report:

> "One of the most powerful initiatives emerging from the task force AWE was situational awareness. Using appliqué computers and the tactical internet, unit commanders, small unit leaders, and individual vehicles were able to share information about both friendly and enemy forces, reducing the historical fog of war." [7]

As expected, making new technologies suitable and effective for the human component of the system (i.e., the warfighters) presented several challenges. Warfighters, who had received extensive training over the course of their careers in the "old" way of conducting combat, initially resisted the insertion of FBCB2 into their combat platforms, because this insertion required a significant change in tactics, techniques, and procedures (TTPs). According to the research conducted by the Army Research Institute in 1997,[25]

> ". . . as soldiers and leaders became more familiar with the technology and its use, they became less threatened by it, and appreciated more the positive impact it would have on them, their units, and the Army as a whole."

By the 1998 Limited User Test, both technical performance and warfighter acceptance were considerably higher. By 2003, based on the lessons-learned report[8] from the initial use of FBCB2 in heavy combat operations, there was enthusiastic and wide acceptance. The concurrent technology maturation and increase in user acceptance that was achieved over time is always desired, but seldom realized.

With FBCB2, the core of the desired technical capability was real-time situational awareness. LTG Thomas Metz, who at the time of the original experiments was a colonel in the tactical unit that formed the experimental force, stated in a 2006 article:[26]

> "At the heart of this experiment was near real-time location knowledge of friendly units down to individual vehicles and in some cases, individual Soldiers. The experiment proved that "Where I am" and "where my buddies are" is powerful information for combat leaders. Leaders at all echelons became convinced that information-age technology would help our soldiers, leaders, and formations become much more capable."

FBCB2 achieved a formal low-rate initial production decision milestone in approximately three years – practically unprecedented for a new complex weapon system. The system achieved a unit-cost well below the unit production cost target. User assessment showed that the resultant system was deemed easy to use. In fact, the training time required during the initial major combat deployments was far ***less*** than that originally envisioned.

5.2. Critical Success Factors and Lessons Learned

FBCB2 showed that a complex development that incorporated multiple simultaneous scientific, technological, doctrinal, training, and human-factors advances could in fact succeed, and do so within a modest and predicable time-frame and budget. Key factors that contributed to this success included: (a) a strong, top-down commitment within the Army to the program, including the willingness to do several off-nominal things to achieve success (e.g., allow the development contractor access to actual operational tactical units, go forward to certifying authorities with a radical new network security model, and so forth) (b) establishment and utilization of a formal experimental methodology (c) empowerment of the development team to implement a number of methodological innovations, in conjunction with all of the technological innovations (d) a willingness to carry multiple options in the design trade-space for an unusually long time to mitigate a significant portion of each risk item before down-selecting to a single preferred approach (e) a willingness to push experiments to the point of failure, to uncover behavioral boundaries (technical, scientific, human-factors) (f) a willingness to manage the program with schedule as the independent variable, and being willing to adjust the order and timing of specific capabilities to keep on schedule. Adhering to schedule was vital for making the interaction with the operational tactical units effective (because of the inflexibility in their planning schedules). Several of these points were recognized in an Army Science Board study conducted in 2007. [6]

5.3. Civilian Sector Benefits

The benefits of the FBCB2 system go beyond the military, extending into the civilian sector. For example, many of FBCB2's capabilities have found their way into consumer electronics. Specifically, FBCB2 pioneered the field of GPS-enabled mobile devices. FBCB2 was the first system to optimize internet unicast protocols (e.g., TCP) for use on low-bandwidth, wireless network.[27] FBCB2 invented many of the core concepts now in wide use for performing security administration and control tasks remotely (e.g., remote lock and/or erase of a mobile device).[28,29] FBCB2 invented techniques now widely emulated for managing and administering a large network of wireless devices.[29] And, finally, FBCB2 invented techniques for increasing battery life on GPS-enabled devices.[30]

5.4. Path Forward

In 2003, a variant of the system was introduced that made use of direct-to-satellite communications links, in addition to the line-of-sight radio links of the original version. This variant is more effective in support smaller, less-dense deployments, and operations in complex terrain, where line-of-sight make be obscured. Recently, a single shared version has been adopted by both the Army and the Marine Corps. Other recent changes include integration with a wide range of battlefield devices, ranging from vehicle sensors to small unmanned air vehicles.[31,32]

Recently, advances made in platform-based engineering[31], systems integration[33], and systems-of-systems integration[34] can be expected to further advance the capabilities of the Digital Battlefield. Also, advances in elegant systems design and engineering[35] will become key enablers of dealing with complexity on the Digital Battlefield.

6. Approval for Public Release

The descriptions of the FBCB2 system included in the above were cleared for public release by the Army FBCB2 project office and the U.S. Army Security Office at the Aberdeen Proving Grounds, 1 April 2011, for use in Siegel, 2011.[10]

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