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Robert R. Hoffman, Timothy M. Cullen & John K. Hawley

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ABSTRACT
A primary motivation for developing autonomous weapons is the assumption that such systems require fewer combatants with lower levels of expertise, thus cutting costs. For more than two decades, the Defense Department has employed highly automated weapons, including the Patriot air defense system and the Predator aircraft system. For the myths of automation to hold, the human costs of the systems should have fallen as the Army and Air Force became more accustomed to them. But automated weapon systems have actually required more highly trained and experienced experts, and the failure to train personnel to operate the systems adequately has led to fratricide and the loss of innocent life. The Defense Department needs to improve its policies on the procurement and development of automated systems if the weapons are to be responsive and effective in future conflicts.

KEYWORDS
Patriot air defense system; Predator aircraft; autonomous weapon; fratricide; automated weapon systems

As the US military has led interventions and subsequent low-level conflicts in various regions over the last two decades, other nations have developed advanced capabilities to deny and contest American military operations. Integrated air and sea defenses, advanced electromagnetic systems, and long-range ballistic and cruise missiles have threatened to deny the Defense Department the ability to confront America's enemies. Russian President Vladimir Putin's planned deployment of the highly capable and automated S-400 antiaircraft system to Syria is a recent example of the trend (Taylor 2015). The Defense Department views automation as a technology that US military services could use to "break out of current limitations" (Office of Technical Intelligence 2015, iii). With the promise of automation, the military services hope to develop "game changing technologies" that can react faster, endure longer, and operate farther away from their bases, in increasingly dangerous and complex environments (Department of the Air Force 2015a, 59; Office of Technical Intelligence 2015, 6).

On the one hand, the Defense Department's vision on fulfilling the promise of automation includes the development of intuitive "human-machine interaction technology," "synergistic airman-autonomy teams," and other concepts that the human systems integration community has presented to the services since at least 2001 (see Society of Naval Engineers 2001; INCOSE 2006; Simpson 2006; quotations are from Office of Technical Intelligence 2015, 11; Department of the Air Force 2015b, v; Defense Science Board 2012). On the other hand, the Defense Department's advocacy and justification for weapon systems autonomy is based on beliefs about the potential of automation to decrease costs, while at the same time replacing humans (Office of Technical Intelligence 2015, 6–9). According to the Defense Department's Autonomy Community of Interest report (Bornstein 2015), the main drivers of the Department's science and technology research are efficiencies that "reduce human footprint and personnel cost" (6). The Air Force's vision for automation includes the development of remotely operated and autonomous platforms and the capability to strike targets from long range, which the service hopes will "decrease the size of the necessary expeditionary force" and result in a more diverse workforce (Department of the Air Force 2015a, 46).

The Air Force's strategy for developing autonomous weapons is consistent with the Defense Department's earlier visions for automation, which argued that the systems would require fewer combatants and, in some cases, eliminate human involvement altogether. To be sure, elements within Defense are aware of the issues and implications of autonomy in warfare and are unsure how to incorporate human decision-making into the operation of the systems. Concerns about machine control have indeed compelled the Department to require the military services to incorporate the authority of human operators in the design of automated weapons. But the myths of automation are rarely questioned (DoD Directive 3000.09 2012). A primary motivation for developing autonomous

CONTACT Robert R. Hoffman rhoffman@ihmc.us

weapons is the assumption that such systems will not only require fewer combatants, but will need combatants of lesser expertise, thus cutting costs. According to this belief, automated systems should work faster, better, and cheaper (Bradshaw et al. 2013).

As we argue through the course of this essay, that belief is a myth, a reflection of the unbridled enthusiasm of technologists.

For more than two decades, the Defense Department has employed highly automated weapon systems in combat to defend friendly forces from attack and to observe and kill adversaries from long range in hostile environments. These weapon systems include the Patriot missile system, which has the ability to select, engage, and destroy aircraft and missiles automatically, and the Predator aircraft system, which can fly from point to point and observe objects on the ground automatically. For the myths of automation to hold, the human costs of the systems should have fallen as the Army and Air Force became more accustomed to the operation and sustainment of the systems.

But greater automation has not resulted in a corresponding reduction in the quantity and proficiency of trained warfighters. Indeed, automated weapon systems have required more highly trained and experienced experts, and the failure to train personnel to operate the systems adequately has led to fratricide and the loss of innocent life. While automated weapon systems have enabled the US military to conduct highly effective missions in unprecedented ways, the Defense Department needs to improve its policies on the procurement and development of automated systems if the weapons are to be responsive and effective in future conflicts.

Problems with the Patriot

The Patriot air defense system is one of the first US weapons to employ "lethal autonomy," which refers to systems that are able to apply lethal force with minimal or no human oversight. During Operation Iraqi Freedom in 2003, Patriot missile systems successfully engaged nine enemy tactical ballistic missiles. But two other engagements resulted in fratricide when the system mistakenly identified friendly aircraft as enemy missiles.

In the first fratricide incident, the Patriot system misclassified a British Tornado fighter-bomber as an anti-radiation missile, launched its own missile at the aircraft, and killed the two crewmembers onboard. After the accident, Patriot units put all the launchers in theater into a "standby" status in the automatic mode. While in standby, operators had to return one or more of the launchers to "ready" status before the system could automatically engage a target. By putting the system in standby, Patriot operators modified the status of the system to obtain a second look from a human before it could engage an incoming aircraft or missile.

Despite the new procedures, another Patriot system engaged a Navy F-18 and killed its pilot shortly after the first fratricide incident. Less than a month after shooting down the British fighter aircraft, a Patriot system generated indications of a ballistic missile attack because of radar interference. Responding to those indications, the tactical director ordered his crew to "bring your launchers to ready" (Hawley and Mares 2012). The director wanted his crew to prepare for a potential response, but his crew changed the status of the system from a "standby" to a "ready" status instead, which allowed the automatic mode of the system to launch a missile against the indications of the incoming ballistic missile. Unfortunately, the indications were false, and when the Patriot missile approached the area of the false indications, sensors on the missile found and engaged the F-18 instead.

After the two incidents and the tragic loss of three lives, senior Army commanders expressed their concern over the apparent "lack of vigilance" on the part of Patriot crewmembers along with the "unwarranted trust in automation" and apparent "lack of cognizance" of what the system displayed to Patriot crews (Hawley and Mares 2012). To the commanders, the operators of the system were primarily responsible for the incidents, but an investigation by the Army Research Lab revealed other causes:

- **Blind faith in automated systems**. Emboldened by what supporters saw as Patriot's flawed but strategically successful engagement of ballistic missiles during the First Gulf War, Patriot's organizational culture and command structure emphasized reacting quickly, engaging early, and trusting the weapon system with little question.
- **Failure to compensate for changes in modes of operation**. Patriot missiles are very lethal, and early Army policies advocated against using the system in automatic mode, which automatically selected and launched missiles at targets. When the Army employed the system against ballistic missiles in addition to aircraft, however, Patriot units had to operate the weapon in automatic mode for the system to be responsive and effective against rapid attacks. The Patriot community did not alter its operating concepts to account for the change in employment method.

- **Failure to retrain for new roles**. The Patriot community also did not adapt its training regimen adequately to operate the system in automatic mode. With the change in mode, the role of Patriot crewmembers transitioned from a more traditional operator to a supervisor-controller who managed the automated engagement routines of the system. Patriot crewmembers became supervisors of a highly automated process, which required them to monitor the system for correct performance and respond to system cues intermittently when necessary. Patriot crews did not understand completely how anomalies could affect system performance as a whole and increase the risk of fratricide.
- **Unaddressed system fallibilities**. A series of operational tests starting in the 1980s highlighted the propensity of the Patriot's autonomous mode to misclassify targets, which included mistaking aircraft for ballistic missiles. The manufacturer was unable to solve the problem in subsequent software upgrades, and the Patriot community did not sufficiently alter its operator training, doctrine, crew procedures, or standard operating procedures to address the tendency.
- **Failure to keep operators informed**. The Patriot community did not ensure that all of its operators knew the limitations of the weapon system involving the identification of targets, and the training program for Patriot operators did not address the system's misclassification problems until after the fratricide incidents.
- **Failure to train for expertise**. Rather than emphasizing adaptive problem solving and critical thinking, the Patriot community's approach to operations training was similar to the methods used to train personnel on system movement and setup – tasks which required much less skill and knowledge to employ and monitor the weapon during operations. Operator training was much too short to develop the proficiency needed to adapt to the evolving mission of the system, and after Operation Desert Storm, the Army reduced the system's training regimen and the required experience levels for certified Patriot crews. As one officer explained, "We thought that automation did not require well-trained crews. I guess we were wrong" (Hawley 2011).
- **Inappropriate job assignment**. The Army's practice of assigning inexperienced personnel to key positions in Patriot crews and the community's administrative tendency to rotate crewmembers into staff positions shortly after arrival to a unit inhibited the ability of Patriot systems to adapt to dynamic situations. The operators participating in Patriot engagements were often the newest and least experienced personnel in the organization, and they rarely remained on the job long enough to learn how to employ the system adequately in the field.

When the Patriot missile system engaged and killed friendly aircraft in 2003, the crewmembers performed in accordance with what the Patriot community emphasized and reinforced in their training: trust the weapon system. The crewmembers' limited experience with the system conditioned them not to question the machine's recommendations, which weapons designers, software engineers, and others built into it. They placed the crewmembers in the control loop merely to monitor the engagement process and to override the weapon only when the crewmember determined that the system's engagement logic was inaccurate. Research and operational experience indicate that this is a difficult role for humans to perform adequately, especially if the operators have limited experience and only a basic understanding of how the system works (Woods and Hollnagel 2006).

When crewmembers began to employ the Patriot more often in the automatic mode, policymakers in the community succumbed to another of the myths of automation: Increased capability in an automated system corresponds to reduced workload for the humans interacting with it. Automation became synonymous with notions of a self-sufficient and self-directed machine that presumably requires fewer expert operators at potentially lower cost to the organization. Experience with the Patriot in combat revealed just the opposite. Control of increasingly advanced and automated technology often requires greater understanding, training, and proficiency – not less. The Army Research Laboratory's reporting on the fratricide incidents recommended that the Army re-examine the level of expertise required to employ weapon systems like the Patriot on the modern battlefield and invoked the concept of "training for expertise" rather than just training (Hawley and Mares 2012). Not unlike the development of genuine expertise with other complex systems, Patriot crews could perform their missions effectively only after considerable practice in difficult and challenging situations (Hoffman et al. 2014).

Predator and its unintended prey

In 2010, US Special Operations forces were clearing a bazaar of weapons and explosives when the ground crew of a Predator, an unmanned reconnaissance aircraft the Air Force did not begin to arm with missiles until late 2000, spotted a convoy of trucks heading toward an Afghan town. The appearance of the group matched intelligence information about enemy reinforcements, and the leader of the Special Forces team called in a pair of helicopters to destroy the threat with missiles and rockets. When the helicopter pilots wheeled around for a second attack, they noticed a "flash of color" from the occupants in the vehicles. Fearing the colors indicated the presence of women, the pilots stopped their attack (Naylor 2010). Tragically, the targeted individuals were not Taliban insurgents trying to outflank the Americans. The travelers were on a journey to Kandahar for supplies and medical treatment, and the attack killed or injured 35 civilians. An investigation of the incident, led by a major general in the Army, blamed the casualties on the "inaccurate and unprofessional reporting" of Predator crewmembers who "ignored or downplayed information that the convoy was anything other than an attacking force" and "deprived the ground commander of vital information" (Zucchino 2010; ISAF 2010).

The tragedy and subsequent indictment were manifestations of Predator operators' worst fear – that they would be perceived only as amateur sentinels monitoring a highly automated aircraft. Not unlike Patriot operators in 2003, Predator pilots, sensor operators, and intelligence personnel struggled with their automation. In contrast to the Patriot missile system, however, the Predator community had spent more than a decade transforming the capabilities of the weapon system, the interactions of operators and automated machines within the system, and the professional relationship of Predator operators with the greater warfighting community, all in order to avoid such incidents and recriminations. The catastrophe highlights the importance of practice and expertise in the operation of automated systems and the cost and extent of such efforts. It also highlighted problems similar to those seen in the Patriot experience:

- **Blind faith in automated systems**. After almost 14 years of experience in combat with the aircraft, Predator operators were under no illusions of the efficacy of automation for remote flight in 2010. The Israeli aircraft designer Abe Karem and engineers in Leading Systems and General Atomics, the primary contractor for the Predator, incorporated automated modes for the operation of the system, hoping to reduce aircraft weight, maximize endurance, and secure communications among components of the system, which included human controllers sitting at their workstations. Transparency, understanding, and reliability of the operating system were of tertiary importance compared to the speed and cost of system development. After typing in waypoints for a mission, early Predator pilots only monitored the subsystems the aircraft needed to stay airborne. As the General Atomics engineers improved the reliability of the workstation for the aircraft, pilots often listened to music, read books, or took naps during their shift in the management of a flight. Not until the Predator community put Hellfire missiles on the aircraft and procured the larger and more lethal Reaper did Predator operators address the question of how automation induced the inattention of Predator pilots. By 2005, operators began to mandate the active management of automated modes and the drill of crewmembers during the lulls of a mission (Cullen 2011).
- **Failure to compensate for changes in the mode of operation**. When the Air Force took control of the Predator program in 1995, the service's original plan was for the system to compliment the U-2 Dragonfly and address the service's gap in airborne reconnaissance. Early support of Predator missions was similar to the U-2 Dragonfly in both size and function, but by 2010, up to 160 personnel were required to process Predator full-motion video for "customers" such as the special operations community. Predator's flight crews, mission crews, distributed crews, operations centers, and other support personnel interacted with automated systems in addition to accomplishing highly specialized tasks, which included calling out activity observed from Predator video or typing what was said into military chat rooms (Cullen 2011). The Predator community needed to be aware of those interactions to help define the problem, to contextualize video and other information from the system, to distribute information to their customers as needed, and to strike targets. Predator crews could not accomplish their missions without automated modes of operation, but the community viewed their contributions as more effective when they relied on social connections with other warfighters.
- **Failure to re-train for the new role**. The Predator community was well aware that additional training was required to provide intelligence or employ weapons on call or via chat. They adapted their training programs to fulfill insatiable demands for the incredibly detailed surveillance video they

could produce. By 2004, Air Combat Command no longer required Predator pilots to know how to take off or land the aircraft before they flew combat missions. By 2010, sensor operators for the Predator did not have to attend six months of training in imagery analysis before they could become part of the flight crew with the pilot.[1]

- **Unaddressed system fallibilities**. The antiquated status of the Predator's ground control station was legendary in 2010 and remains so today. Predator operators practice for days to gently bank the aircraft or tenderly slew the sensor ball with a spring-loaded stick designed to be gripped by the entire hand (Cullen 2011). The Air Force continues to employ the outmoded interface because of higher priorities – the minimization of development costs and uninterrupted operations. Even the computer-generated interface for the Predator proved extremely difficult and costly to improve.[2]
- **Failure to keep the operators informed**. As late as 2010, a common complaint in the Predator community was the poor state of the system's operations manuals and checklists – even after immense efforts to create and improve them (Cullen 2011). Due to a professional chasm between the civilian pilots developing the system and the military pilots employing the system for the Air Force, Predator operators did not have operations manuals or system checklists until 2000. The manual for the system was over 1,000 pages long, and it cost the equivalent of two Predator weapon systems to develop the documents.
- **Failure to train for expertise**. Air Force leadership understood that experience was critical to the success of the Predator program, but the lack of accurate manuals and restricted access to the weapon hampered the ability of Predator operators to practice the modes and operational routines of the weapon firsthand. Expertise with the weapon system was always of secondary importance to development cost and short-term performance – especially prior to the system's participation in the global war on terror.[3]
- **Inappropriate job assignment**. When the Air Force created its first Predator squadron in 1995, the service mandated that only experienced pilots and navigators fly the aircraft, but before September 11, 2001, the developmental nature of the program restricted their access to the system and to other expert operators. After 9/11, the Predator community was able to transform the job, and automated systems were essential to the evolution of Predator operators from "stick monkeys" and "lepers" who only gathered and passed information to "warfighters" who could integrate information and kill enemy combatants from secure and interconnected locations in the United States (Cullen 2011). From 2003 to 2005, the Predator community moved their remote operations to the United States to facilitate access to secure intelligence networks, and Predator crews used up to six flat-screen monitors they bolted onto the ground control station to manipulate network applications, mapping tools, and instant messaging programs on a mission. These tools, which were not officially a part of the Predator system, enabled Predator aircraft armed with Hellfire missiles and a geo-stabilized sensor ball to not only observe enemy behavior but also to interpret that behavior, coordinate responses, and attack threats when desired. Automation allowed the Predator community to demonstrate a valued capability, but the capability could not have been possible without a larger network of highly specialized people, even more machines, and even more software.

The reality of automation

Both the Patriot missile and Predator aircraft systems have lived up to some of the promise of automation. They have given the armed forces the ability to react quickly to ballistic missile attacks and to observe and kill insurgents from continents away. But the human cost savings incurred after decades of experience with these weapons programs remains mythical.

Automation does not necessarily reduce manpower requirements in either the quantity or quality of trained personnel needed to employ a weapon system effectively. On the contrary, automation can increase the importance and number of people who design, program, guide, and supervise automated systems. Indeed, the notion that automated systems are autonomous is a fundamental myth. Automation can facilitate varying degrees of self-directedness and self-sufficiency for components of the systems in specific contexts, but *interdependence* defines the relationship between the human and machine elements of the weapons. Automated weapons systems have increased the power and responsibility of weapons designers, programmers, and supervisors and have blurred distinctions between the design and construction of weapon systems and the use and operation of them.

Understanding the architecture, programming, and operational environment of automated systems has become critical to predicting and assessing system behavior. So operator involvement in the design, prototyping, and testing of the systems has become an essential element of effective weapon performances. The requirement for deep involvement of the "end user" in the development, procurement, and sustainment of computerized work systems has been an ardent plea of human factors engineers for many years because alternative "designer-centered-design" philosophies have resulted in systems that were unusable and barely comprehensible, and led to shockingly huge wastes of taxpayer money (for examples, see Hoffman and Elm 2006; Hollnagel, Woods, and Leveson 2006; Woods and Hollnagel 2006; Zachary et al. 2007). Designer-centered design is a process in which program managers and organization leaders – although experienced, intelligent, and well intentioned – believe that they can identify with the individuals who will actually do the work that they have re-invented, often with very little interaction with the warfighters themselves. When designer-centered design processes do involve end users, they often do so only at the end of a development program when system developers conduct a simplistic and insufficient procedure called usability analysis (Bias and Hoffman 2013).

The involvement of warfighters in the development of autonomous weapon systems is especially important given the Defense Department's policy on the design of the systems: "Autonomous and semi-autonomous weapon systems shall be designed to allow commanders and operators to exercise appropriate levels of human judgment over the use of force" (DoD Directive 3000.09 2012).

Experience with the Patriot and Predator weapon systems reveals, however, that it is costly and difficult to incorporate the judgment of responsible commanders and experienced operators when assumptions about how and under what context combatants should employ the weapons are designed into the systems and hidden deep inside them. "Appropriate levels of human judgment" are dynamic and negotiated among components of the system, both in battle and over the entire life cycle of a weapons program. By its very nature, the discussion is a human-intensive and costly process.

The dynamic duo: humans and machines, working together

Autonomous weapons systems have become a ubiquitous component of the modern battlefield. With a few exceptions, the US military has successfully employed weapons such as the Predator and Patriot systems to attack and observe America's enemies persistently from great distances and to respond to airborne attacks quickly and decisively. The Defense Department views advances in automation as an opportunity to execute these missions against emerging threats in an increasingly contested environment and, critically, at a reduced cost. For automated systems such as Patriot and Predator to operate effectively, however, the communities around those systems had to negotiate their roles and the role of other associated entities for the systems to perform adequately in combat.

For the Patriot and Predator weapon systems to achieve acceptable levels of performance, cost, and risk of failure, stakeholders in the systems negotiated how human and machine elements of the systems were to work together. Often the resulting advantages included the ability of machines to process large amounts of data quickly and consistently and the ability of humans to recognize patterns of behavior, reason analogically, and adapt to novel situations. After examining these negotiations and system operations – which often involved the execution of tasks and missions beyond the scope of the systems' original design – we identified two important characteristics of autonomy in military applications: Automation does not remove the need for human decision-making from real-time operations; and the "system" is not just a machine, but an assemblage of interacting machines, people, and operational practices.

Both the Patriot and Predator systems had the ability to operate in what others may describe as a completely autonomous mode, but both communities using those systems chose to employ them in fully autonomous mode only in very specific circumstances. In most cases, the system could accomplish more with less risk when humans and machines operated as a dynamic team. Humans remained essential components of the system, and the incorporation of automated modes did not translate into reduced risks of failure – especially when team members did not understand how the technology worked in practice. Contrary to myth, the execution of automated warfare often required *more* people, possessing *greater* expertise, and timely interactions with the internal functions of the systems, if the weapons were to be used effectively.

The interdependency of humans and machines in the use of autonomy increases, not decreases, resource requirements. To get a grip on the cost and risk of future autonomous weapon systems, the military services should include warfighters and system operators throughout the design and development processes. Automated weapon systems have not utilized "machine judgment" to select or engage targets in Afghanistan, Iraq, or any other electronic battlefield. System engineers, software developers, computer programmers, and others incorporated their judgments into the design, construction, and operation of the weapons, and their actions and assumptions about how and under what conditions the military was going to use the systems determined how the weapons selected and engaged targets for destruction.

Those who are most familiar with the combat environment – warfighters – should be intimately involved in the development of automated weapon systems, and the Defense Department should create policies to ensure operators' participation in weapon design. For example, after a 2012 report on autonomy by the Defense Science Board, the Defense Department created an "Autonomy Community of Interest," which was to identify potential investments, to initiate technological developments, and to engage in multi-agency cooperation toward greater weapons autonomy. Unfortunately, that collaborative framework is for "scientists, engineers, and acquisition personnel" – not warfighters (Bornstein 2015, 5). The operators of automated weapon systems should be active participants in the Autonomy Community of Interest, and weapons designers and operators should also incorporate the insight of contemporary warfighters into system functions and interfaces through proven techniques developed by cognitive systems engineers (Crandall, Klein, and Hoffman 2006; Hoffman and McCloskey 2013; Hoffman et al. 2010).

Current Defense Department policies do not encourage or adequately value the development of operator expertise as an essential component of autonomous weapons acquisition. For example, the department's personnel policy for human-systems integration in weapons acquisition states that "to the extent possible, systems will not require special cognitive, physical, or sensory skills beyond that found in the specified user population" (DoD Instruction 5000.02 2015, 118). This limited and simplistic policy discourages program managers from approving initiatives that foster operator expertise, and program managers can use the policy to justify the complete dismissal of all expert operators currently supporting a weapons program – an event the Predator community experienced twice. Predictably, when tragedy happens, the operators get blamed.

The Defense Department's directive on autonomy also states that "systems will go through rigorous hardware and software verification and validations" so the weapons can "function as anticipated in realistic operational environments against adaptive adversaries" (DoD Directive 3000.09 2012, 2). This incomplete policy assumes the Defense Department can verify and validate the performance of autonomous systems without certifying the performance of the weapons' human operators, training programs, and tactics. The Department's view of autonomous systems as interdependent teams of humans and machines working together toward common goals is laudable. But defense policies on the development and evaluation of weapon systems must include certified human operators and the development of operator expertise as crucial requirements before warfighters, commanders, and the public will trust the employment of autonomous weapons against advanced foes.

In a 2015 report on autonomy, the chief scientist of the Air Force called for a new approach to the design of autonomous systems and described a vision for the development of "synergistic human-autonomy teams," which the air service could use to meet "the challenges of a newly forming adversarial environment" (Department of the Air Force 2015b). We humbly submit that the Defense Department's "new approach" to autonomy should continue to emphasize the interdependence of humans and machines in the employment of autonomous systems. But the perspective by itself is insufficient unless it is carried over into actions. The military services should also facilitate the active participation of warfighters in the design and development of the weapons, acknowledge the importance of operator expertise in the effective performance of the systems, and concede the critical contributions of humans in the real-time employment of even "autonomous" weapons.

Finally – if experience with the Patriot and Predator systems is *any* indication of the cost and risk of highly automated weapons – the improved capabilities of additional autonomous systems will not come cheaply. Development of the systems will be for naught without the testing, validation, and practice necessary to operate the weapons in dynamic environments confidently and without time-consuming negotiations among program managers, engineers, software developers, operators, and commanders. Given current fiscal constraints, we are skeptical of the military services' ability to execute any of the above initiatives successfully. At best, development of the systems without adequate resources will lead to the mass production of obsolete and unusable weapons. More likely, the development of autonomous systems on an irrational budget will lead to mission failure and the loss of innocent life.

Notes

1. Experienced sensor operators also alternated between automated and manual modes of image optimization and stabilization to change the iris settings and focal length of several different types of cameras to examine the depths of shadows and sources of color from a

scene. Operators felt they had to manipulate video from the Predator's sensor ball to characterize minute details of events below the aircraft. Unfortunately, they had to do so using a throttle quadrant from a crop duster and a control stick from a crane (Cullen 2011). The Air Force was also funding the design of an "advanced cockpit" in 2010, which eliminated the position of the sensor operator altogether (General Atomics 2011). Pilots in the proposed cockpit would have to control the aircraft and the sensor ball with a throttle quadrant and control stick from an F-16 Fighting Falcon – a highly maneuverable fighter aircraft. Prior practice with the current weapon system seemed to have little influence on the design and improvement of the system's interface.

2. It took over a decade for the Predator community to update the heads-up display for the aircraft, and engineers based the display's green symbols and representations of tape instruments on the heads-up display for the F-16. Again, improvements to the system seemed disconnected from experience until 2010, when an improved display allowed operators to control and monitor the performance of the aircraft without obscuring the crew's view of the ground.
3. Helicopter pilots in the US Army were the first to use the Predator in combat, and in 1996 they taught the Air Force's first Predator operators how to use the system without an operations manual, flight checklist, training regimen, or simulator (Cullen 2011). Before their assignment to the new squadron, the Air Force pilots had never heard of the Predator, but immediately after their training, the handful of former transport pilots replaced the Army personnel flying the Predator in combat over the Balkans. The most combat-experienced operators of the system did not contribute to its employment or development ever again. After gaining control of the Predator program from the Army, the Air Force hired a completely new cohort of contractors to develop courseware and provide in-flight instruction for new Predator pilots. Many of them were retired F-14 Tomcat operators. In 1999, the company lost its training contract to a competitor, which did not hire a single experienced operator from the old company to build its new instructor corps. The same year, the Air Force flew a Predator with a new sensor ball and laser designator in combat over Kosovo, but the service did not allow members from the Predator squadron to fly the missions and gain valuable experience with the system (Cullen 2011). Throughout the evolution of the Predator, the development and sustainment of expertise was of lower importance than control of the program and the demonstration of combat capability at low cost.

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Notes on contributors

Robert R. Hoffman is senior scientist at the Institute for Human and Machine Cognition. Specialties are human-centered computing and work system design. His doctorate is in experimental psychology (University of Cincinnati). He is a Fulbright Scholar; fellow of the Association for Psychological Science; and fellow of the Human Factors and Ergonomics Society. His latest book is *Accelerated Expertise* (2014).

Col. Timothy M. Cullen is a professor of strategy and security studies at the School of Advanced Air and Space Studies, Air University, Alabama. He received his doctorate in engineering systems from the Massachusetts Institute of Technology in 2011. Cullen is also an F-16 pilot with over 250 hours in combat over Bosnia-Herzegovina, Serbia, and Iraq.

John K. Hawley is an engineering psychologist with the Human Research and Engineering Directorate of the US Army Research Laboratory, Ft. Bliss, Texas. He received his doctorate in psychology from the University of North Carolina at Chapel Hill in 1977. He has written more than 100 professional articles, technical reports, and book chapters on human-systems integration and performance in complex military systems.

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