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Advantages and challenges of unmanned aerial vehicle autonomy in the Postheroic age

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Advantages and Challenges of Unmanned Aerial Vehicle Autonomy in the Postheroic Age

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Abstract

Over the past decade, unmanned aerial vehicles (UAVs) have revolutionized how the U.S. engages elusive militants in low-intensity conflicts by allowing the U.S. to project continuous military power without risking combat casualties. While UAV usage promises additional tactical advantages in future conflicts, little agreement exists regarding a strategic vision for UAV research and development, necessary for the U.S. to allocate limited resources among UAV development programs that address national security objectives. The present research makes the case for a future UAV technology evolutionary path leading to fully autonomous intelligence, surveillance, and reconnaissance (ISR)/strike UAV systems for the United States Air Force that are capable of sensing their environments through multiple modalities, recognizing patterns, and executing appropriate actions in response to their real-time analyses. The thesis addresses enabling technology inroads stemming from major improvements in our understanding of human neural circuitry that promise to enable innovations in the artificial intelligence needed to achieve autonomous system function. Arguments are based on projected military and economic benefits of autonomous systems and extend the historical model established by the CIA's successful UAV program to unconventional warfare (UW) conflicts that the U.S. Air Force finds itself ill-equipped to handle. Counter-arguments are addressed relating to uncontrolled lethal technology, conflict initiation thresholds, and the vulnerability of overreliance on high-technology systems. In making the case for fully automated UAV technology, research provides a strategic future vision for autonomous UAV usage by highlighting the important interaction of artificial intelligence, "smart" wide-area sensors, and cooperative micro UAVs.

1.0 **Introduction: Welcome to the Postheroic Age**

"Wonder weapons... my God, I don't see the wonder in them. Killing without heroics, nothing is glorified... nothing is reaffirmed? No heroes, no cowards, no troops, no generals? Only those who are left alive and those who are left dead. I'm glad I won't live to see it."

-*Patton* (1970 Film)

In this 1970 biographical dramatization, General George S. Patton gives this response when asked about his opinion of Germany's advanced technological military pursuits throughout World War II. Patton's remarks were mostly directed at V-2 rockets, push-button bombing, and atomic weapons. Such weapons represented "wonder weapons" because they could be directly used to strike an enemy's strategic targets, such as population centers, while largely bypassing direct ground engagements with the enemy's armed forces. Additionally, these weapons' long range and high yield allowed targets to be attacked while significantly reducing friendly forces' exposure to danger. For example, Germany V-1 rockets killed 5,475 civilians and injured 16,000 more in a string of attacks on London during World War II.[1] Such rockets were safely fired from mobile launchers in German-occupied territory. The atomic bombing of Hiroshima and Nagasaki further illustrated this point, forcing the Japanese to surrender and allowing the U.S. to avoid a costly invasion of the Japanese mainland that was estimated to result in one million allied casualties. Such weapons firmly entrenched the new era of strategic warfare in the world's collective military capabilities.

Although no one knows if Patton actually uttered the exact quote from the film biography, his belief that courageous, disciplined, thoroughly trained soldiers were the key to military victory is well documented.[2] Thus the real General Patton would likely have agreed that the introduction of

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[1] The National Archives, Accessed March 2nd, 2012
[2] For a thorough biography on Patton, please refer to D'Este, 1995

strategic weapons was undesirable, as these weapons devalued the importance of the disciplined fighting soldier, self-sacrifice, and heroism in warfare. In some forms of strategic operations, a soldier's direct involvement has been largely relegated to planners, initiators, and observers, deferring the actual risks and destructive capabilities solely to advanced technologies.

Roughly six decades following the end of World War II, a new class of wonder weapons has been silently maturing throughout the last decade of conflict. Superficially, these new weapons resemble updated versions of age-old conventional military vehicles, mostly airplanes and helicopters. Similar to their conventional counterparts, these new weapons can carry out intelligence, surveillance, and reconnaissance (ISR) missions, engage enemy forces with precision munitions, and transport cargo. However, these modern wonder weapons differ from previous military vehicles in one crucial respect: the new weapons have no human operators onboard, as the human controllers wirelessly manage the vehicles from another location, sometimes thousands of miles away. Because pilots and operators are not physically present, such planes are frequently referred to as unmanned aerial vehicles (UAVs). For perhaps the first time in history, the maturation of UAV technology and its increasing presence in modern conflict has subtly but steadily marginalized the importance of humanity's physical involvement on the battlefield itself, thus continuing the trend that began during World War II. Just as rocketry and nuclear weapons relegated humans to support roles in strategic operations, UAVs are now removing human soldiers from tactical operations as well.

The potential for completely eliminating physical human presence in tactical engagements is particularly significant, as the battlefield has been the historical realm of opposing warriors and soldiers for thousands of years. Indeed, historians attribute the first organized armies to the

Sumerian city-states in Mesopotamia as early as 2500-3000 BC.[3] Violence likely long-preceded organized warfare, as is demonstrated by Jericho's roughly 10,000 year old city wall.[4] From the moment professional armies first organized, military leaders began seeking weapons that provided tactical advantages by increasing the average soldier's lethal battlefield range. For example, roughly five hundred ancient Greek hoplites would be required to effectively cover a battle space the size of a football field.[5] By the American Civil War, military weaponry had sufficiently advanced to the point where only twenty soldiers were required to cover this area. This number decreased to two soldiers during World War I. By World War II, one soldier was capable of covering an area equal to five football fields. In 2008, an average of one U.S. soldier per 780 football fields existed in Iraq.

The introduction of advanced military vehicles, such as airplanes, has simply compressed the window in which some soldiers are exposed to danger. For example, during the Vietnam War, airplane pilots still engaged in some risk when flying missions over the battlefield and could have contracted deadly diseases from the unsanitary, tropical habitat in which they resided.[6] There was also a small chance that their planes could crash during a mission. Thus despite the average increasing distance that one soldier could cover, humans have always faced considerable risks when going to battle, whether they served in a Roman legion or as a Desert Storm fighter pilot.

Although UAV technology may simply appear to represent yet another installment of military weaponry's increasing battlefield reach, this new technology represents a dramatic departure from this paradigm. Until now, no weapon in history has allowed soldiers to avoid tactical battlefield

[3] Sturgeon, pg. 16
[4] *Ibid.*
[5] Singer, pg. 100
[6] Harrison, 1989

risks vicariously by controlling weapons from thousands of miles away. Indeed, in remote split operations, a UAV pilot can instantaneously switch between operating a UAV in Iraq and a UAV in Afghanistan.[7] Thus the "wonder" of UAVs is that their use has freed soldiers from geography's limitations. Consequently, UAV pilots can neutralize targets from remote cockpits by day and dine at home with their families by night, even when their planes crash. The timeless battlefield attributes of courage, sacrifice, camaraderie, and perseverance lose some of their meaning. Without these qualities, some critics may argue that even the smallest tactical operations will result only in "those who are left alive and those who are left dead."

Despite the erosion of romantic ideals associated with UAV usage, this technology is already deeply entrenched in the U.S. military and intelligence community because it provides military leaders with many unique advantages that address current battlefield challenges. Historically, war used to be fought between countries by fielding large armies. Modern 21st century conflicts will become increasingly asymmetric, with large, well-funded forces pitted against smaller insurgent forces of dedicated fighters.[8] Because of their inferior training, numbers, and technological proficiency, insurgent forces will be reluctant to directly engage a country's military, thus increasing the appeal of low tech weaponry that reduces insurgent exposure to danger. The frequent insurgent reliance on improvised explosive devices (IEDs) to attack Coalition Forces in Iraq and Afghanistan represents an example of such tactics. Indeed, by 2009, 75% of coalition combat casualties in Afghanistan were being caused by IEDs.[9] Equipped with such an effective tactic, insurgents have recently adopted the psychological strategy of killing enough occupiers to eliminate the national will to sustain military presence. By removing soldiers from the battlefield while continuing to project military power, UAVs represent the

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[7] Singer, *op. cit.*, pg. 330
[8] "Remote Control War", 2011
[9] See http://www.armytimes.com/news/2009/04/gns_afghanistan_casualties_ieds_040309/

perfect counter to such a strategy of attrition; if humans are not present on the battlefield, then they are not vulnerable to insurgents' asymmetric tactics. Because of the technology's success, the U.S. stockpile has grown from few drones (N.B. the terms "UAVs" and "drones" will be used interchangeably) at the outset of the Iraq invasion in 2003, to roughly 7000 today.[10, 11] Stunningly, the U.S. Air Force trained more UAV pilots than fighter and bomber pilots in 2009. Within a decade, the U.S. Air Force anticipates reducing its fleet of manned aircraft while quadrupling its arsenal of large, multi-purpose UAVs to 536 drones.[12] Since 2006, the Central Intelligence Agency has also waged a highly successful campaign of UAV strikes against al Qaeda and Taliban militants in Pakistan.[13, 14] UAVs have become internationally popular as well, as at least 40 countries have drone research and development programs, and at least 50 countries have drones in their arsenals.[15, 16] As recently as January 2011, the *IEEE Spectrum* listed drones as the 7th top technology of the decade.[17]

The outlook for UAV near-term growth is promising, with the Pentagon requesting nearly $5 billion for UAVs in 2012.[18, 19] However, long-term funding is more difficult to predict. For example, UAVs are currently being funded through wartime contingency funding instead of the defense budget.[20] Once the wars in Iraq and Afghanistan end, UAVs will have to compete with other manned system projects for defense budget funding.[21] Despite this uncertainty, at least one current projection states that the 2011 global UAV market is worth roughly $7.1 billion and is

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[10] "Remote Control War", *op. cit.*
[11] Bumiller and Shanker, 2011
[12] *Ibid.*
[13] Shultz, 2011
[14] New America Foundation drones database, 2011
[15] Shultz, *op. cit.*
[16] Beidel, 2011
[17] Schneider, 2011
[18] Bumiller and Shanker, *op. cit.*
[19] Erwin, 2011
[20] Erwin, *op. cit.*
[21] *Ibid.*

expected to reach $10.5 billion by 2021, which represents a roughly 4 percent annual growth rate.[22] Cumulative over that ten year span, the total UAV market will be worth an estimated $91.7 billion, with the U.S. expected to account for 69 percent of global UAV purchases. Such growth will occur despite defense cuts and the global economic recession because of the technology's demonstrated value in Iraq and Afghanistan, continued security threats, and the promise that UAVs may someday reduce defense costs. Indeed, given that 9 percent of the defense budget is devoted to paying medical coverage and 45 percent is devoted to payroll and fringe benefits, UAVs could potentially significantly reduce the Department of Defense's personnel-related operating costs to the extent that they ultimately replace humans on the battlefield.[23]

Peter Singer of the Brookings Institute correctly points out that criticizing UAV usage is roughly equivalent to arguing against adopting the personal computer in the 1980's.[24] In fact, the two examples have much in common. Just like the computers of the 1980's, current robotic systems are large, bulky, and cannot perform many functions. In both cases, the military is the chief research and development financier. Today, ubiquitous personal computers are so accepted and commonplace that they are no longer thought of as simply "computers". They are now integrated into iPods, cars, cell phones, watches, and GPS systems among many other consumer products. The U.S. Air Force's Unmanned Aerial System Flight Plan indicates that the next generation unmanned systems will feature multipurpose robots that have standardized airframes with completely modular payloads.[25] Future UAVs will incorporate a wealth of future technological capabilities, such as stealth, solar power, electronic warfare payloads, smaller warheads, sensors,

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[22] defenseWeb, 2011
[23] Erwin, *op. cit.*
[24] "Remote Control War", *op. cit.*
[25] Shaw III, 2010

micro drones, swarming software, hypersonic engines, airborne relay, aerial refueling, and advanced user interface designs, to name only a few.[26, 27, 28] Indeed, Peter Singer noted that UAV technologies are “at the Wright Brothers Flier Stage.”[29] Lt. General Dave Deptula further observed that the state of UAVs today is equivalent to the state of manned airplanes in the 1920’s.[30] Similar to the success of strategic bombing’s meteoric rise in the 1930’s and 40’s, such a metaphor suggests that a UAV technology’s best days lie ahead, as future successes will likely involve a UAV-centric strategic vision not currently embraced by military leaders.[31]

[26] Clapper et al., 2009
[27] Dahm, 2010
[28] Donley and Schwartz, 2009 (United States Air Force Unmanned Aircraft Systems Flight Plan 2009-2047)
[29] Bumiller and Shanker, *op. cit.*
[30] “Remote Control War”, *op. cit.*
[31] See Neillands, 2001 for a review on World War II strategic bombing

1.1 **Thesis Statement**

The present research will make the case for a future UAV technology evolutionary path leading to fully autonomous intelligence, surveillance, and reconnaissance (ISR)/strike UAV systems for the United States Air Force that are capable of sensing their environments through multiple modalities, recognizing patterns, and executing appropriate actions in response to their real-time analyses. The thesis will also address enabling technology inroads stemming from major improvements in our understanding of human neural circuitry that promise to enable innovations in artificial intelligence needed to achieve autonomous system function. Arguments will be based on projected military and economic benefits of autonomous systems and will extend the historical model established by the CIA's successful UAV program to unconventional warfare (UW) and counterinsurgency (COIN) campaigns that the U.S. Air Force finds itself ill-equipped to handle. Counter-arguments will be addressed relating to uncontrolled lethal technology, conflict initiation thresholds, and the vulnerability of overreliance on high-technology systems. In making the case for fully automated UAV technology, research provides a strategic future vision for autonomous UAV usage by highlighting the important interaction of artificial intelligence, "smart" wide-area sensors, and cooperative micro UAVs.

1.2 **UAV History; 1899-2011**

Despite recent headline-grabbing successes of the past decade, unmanned technology's origins can surprisingly be traced back over a hundred years just before the outbreak of the Spanish-American War. In 1898, inventor Nikola Tesla presented a small, remotely-operated boat at New York City's Electrical Exposition at Madison Square Garden.[32] The boat's steering and lighting were both controlled remotely by radio. Although not an unmanned aerial vehicle, this example represents the first known instance of unmanned technology. Several months later, Tesla submitted an article to The Electrical Engineer magazine describing how the same technology could be utilized to create remotely-guided aerial torpedoes, but his paper was rejected because the idea was perceived as being far-fetched. Although fanciful for its time, Tesla's vision for UAV technology was insightful and would ultimately become reality 110 years later when Hellfire missiles could be guided by laser designators controlled either by forward observers or pilots remotely flying UAVs. As early as 1917, the U.S. Navy attempted to use radio-controlled drones to counter German U-boats.[33] During World War II, the U.S. used controllable drones in a limited capacity, and Germany utilized thousands of pulse-jet-powered flying bombs.[34, 35] By 1971, the U.S. military had begun developing its first guided cruise missiles.[36] In 1982, Israel used drones against Syria to locate nearly all of its air defense radar systems.[37] With the exception of the past decade, these early attempts at unmanned technology featured drones that generally relied upon preprogramming rather than real-time human control and were not reusable, thus limiting their usefulness.

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[32] Schneider, *op. cit.*
[33] Schneider, *op. cit.*
[34] Shultz, *op. cit.*
[35] Schneider, *op. cit.*
[36] Barnes, 2009 (UAV Book)
[37] *Ibid.*

In the mid-1990's, General Atomics Aeronautical Systems developed a UAV called the "Predator" to perform Intelligence, Surveillance, and Reconnaissance (ISR) missions.[38] During the Kosovo conflict, General John P. Jumper, commander of U.S. Air Forces in Europe, observed that the U.S. Air Force was having great difficulty effectively acting on targets that had been spotted by Predator UAVs. In what Jumper called "the dialogue of the deaf," UAV operators were frequently unable to provide effective verbal instructions for guiding bomber pilots to spotted targets of opportunity.[39] To correct this problem, Jumper had laser designators installed under the nose of each Predator. These laser designators could be used to highlight targets for bomber pilots and guide "smart" ordinance. Currently, the Predator has logged roughly 950,000 flight hours, making it an early UAV workhorse.[40]

Because of advances in computers and radio links, 2001 featured a breakthrough year for unmanned technology.[41] For the first time, this technology allowed drones to be controlled from afar in real time, thus allowing operators to respond to changing conditions on the ground. During that same year, Israel was the first country to arm a UAV, followed closely by the U.S.[42, 43] Armed UAVs were viewed as a promising force multiplier that could provide new tactical advantages against numerically superior foes.[44] This concept would be convincingly demonstrated by the U.S. later that year.

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[38] Schneider, *op. cit.*
[39] *Ibid.*
[40] Beidel, *op. cit.*
[41] Schneider, *op. cit.*
[42] *Ibid.*
[43] "Remote Control War", *op. cit.*
[44] *Ibid.*

Following the 2001 September 11th attacks, the CIA was granted unprecedented authority to engage in offensive, lethal covert actions against militant groups.[45] The CIA immediately inserted a covert paramilitary team into Afghanistan to establish contacts with the Northern Alliance, a rival group to the incumbent Taliban and al Qaeda militants, and map the front line's GPS coordinates.[46] In a reversal from the Kosovo conflict, human CIA operatives and U.S. Special Forces used laser designators to mark targets for Predator UAVs armed with Hellfire missiles. In less than two months, the CIA-led war defeated an army of 60,000 soldiers and successfully drove the Taliban and al Qaeda from power. Such rapid success against a conventional army at the hands of Special Forces and UAVs changed how modern wars are conceptualized and fought, thus highlighting the role of intelligence-driven warfare.[47] Specifically, the need to kill enemy leadership and destroy enemy safe havens was recognized. The concepts would be expanded upon later in the decade as resurgent Taliban and al Qaeda militants staged an insurgency in Afghanistan.

In 2002, technical refinements allowed control of a Predator to be instantly transferred from one ground control station to another, thus allowing Predators to maintain 24-hour surveillance by staggering the time zones of their operators. This innovation also allowed mission specialization of various operators. For example, the U.S. Air Force operates its UAVs by using overseas personnel to launch and recover aircraft and manages the actual missions by using stateside pilots at Creech Air Force Base, Nevada.[48] On the other hand, the U.S. Army operates its nearly 4000 UAVs by requiring all UAV operators to work alongside troops overseas, even if their job could be handled over satellites from U.S. soil.[49] Presumably, such a policy maximizes the shared war

[45] Shultz, 2011 (Hunt for bin Laden)
[46] *Ibid.*
[47] *Ibid.*
[48] Schneider, *op. cit.*
[49] *Ibid.*

experience between UAV operators and other Army personnel. Also unlike the Air Force, the Army does not require its UAV operators to be officers or have any previous flying experience.[50] This policy is enabled by 2002 advances in specialized radio equipment allowing the use of automated landing software, thus eliminating the need for specialized piloting skills. Indeed, the software is reputed to be more reliable than human pilots. For example, software-controlled UAVs can land flawlessly in blinding Iraqi sandstorms. Regarding the software's effectiveness, Army Sgt. 1st Class Kelly Boehning noted that the U.S. Army's Gray Eagle UAVs – a newer UAV capable of carrying a larger payload than the older Predator UAV model – land "perfectly every time, without exception. It takes some of the fun out, not having the stick and rudder, but it also takes the pilot error out: we don't have any incidents landing – that's where the Predator's downfall is."[51]

UAVs began appearing in strictly conventional combat settings around 2002 and 2003. This time period featured a UAV's first involvement in air-to-air combat when a Predator fired a missile at an Iraqi fighter plane.[52] UAVs also began assuming roles in Operation Southern Watch, which monitored the no-fly zones in Iraq's airspace.[53] One of their major roles was to bait Iraqi fighters and air defense installations, presumably to draw their fire away from manned aircraft and reveal their positions for possible strikes. Ultimately two drones were shot down by surface-to-air missiles, and a third was destroyed by an Iraqi fighter plane. At the beginning of the second Iraq war in 2003, aging, first generation Predators were sent into Iraq to locate targets. If the Predators were attacked, the defender was exposed and vulnerable for destruction. Otherwise, the predators could loiter for days conducting reconnaissance.

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50 *Ibid.*
51 *Ibid.*
52 *Ibid.*
53 Beidel, *op. cit.*

The third generation Predator aircraft, known as the Avenger, is better suited to survive in hostile airspace, such as Iraq's in 2003 and Libya's in 2011.[54] Unlike its predecessors, the Avenger is a pure jet aircraft that first flew in 2009. It can fly up to speeds of 400 knots and can fly at 50,000 feet.[55] The UAV is designed to reduce heat emissions and is shaped in a way that reduces the threat of detection. Lastly, the Avenger can be optionally equipped with a missile warning system.[56]

Another recently developed UAV, the RQ-170 Sentinel, has prioritized survivability to an even greater extent. Known as the "Beast of Kandahar" after being first spotted at Kandahar Air Base in Afghanistan, the Sentinel employs advanced stealth technology to penetrate sophisticated air defense systems.[57] Experts questioned the need for a stealth aircraft in Afghanistan, considering that neither the Taliban nor al Qaeda possess any air defenses or radar systems, and many speculated that the UAV was being deployed against neighboring countries, such as Iran.[58] Such suspicions were confirmed after it was revealed in 2011 that Osama Bin Laden's Pakistani compound had been monitored by an RQ-170 UAV and when an RQ-170 UAV reportedly crash-landed in Iran.[59, 60]

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[54] *Ibid.*
[55] *Ibid.*
[56] *Ibid.*
[57] Hoffman, 2009
[58] *Ibid.*
[59] Beidel, *op. cit.*
[60] Starr, 2011

By 2004, Taliban and al Qaeda militants had fled Afghanistan and established safe haven in Pakistan's lawless, western tribal regions.[61] This situation posed a daunting challenge, because the military had difficulty identifying highly dispersed al Qaeda militants among the civilian population, and their refuge made them virtually immune to overt attack. Because of its unique intelligence-gathering and covert offensive capabilities, the CIA was seen as the agency best-suited to locate and counter this invisible enemy. The CIA created a hit list of militant leaders they planned to target, including Osama Bin Laden, Al Zawahiri, and Mullah Omar, the Taliban leader. Despite the CIA's unique skillset, experts still believed that the CIA had been assigned an impossible task. Greg Miller of the Washington Post summed up the difficult intelligence environment by explaining that the "enemy is highly adaptive. They're moving, in many cases every night, and knowing where somebody is today doesn't help you tomorrow."[62] Before 2004, the prevailing belief was that the Pakistani tribal area was so impenetrable to outsiders that the intelligence would never be good enough to inform a timely covert strike.

By 2004, experts had begun to view UAV technology as the perfect tool for penetrating Pakistan's tribal areas and striking targets. Having been successfully used in the Iraq and Afghanistan wars over the previous three years, drones had acquired a reliable track record as both an ISR and a tactical strike platform. At this time, Predator drones could stalk targets with an array of sensors, including optical, heat, and infrared cameras, all while remaining unseen from 10 miles high.[63] Armed with Hellfire missiles, these drones could be sent into Pakistani airspace to search for targets, as the lack of an American pilot onboard avoided inflaming political sensitivities. Such an advantage became clear in 2008 after U.S. Special Forces

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[61] Shultz, *op. cit.*
[62] *Ibid.*
[63] *Ibid.*

executed an operation in the Pakistani tribal area.[64] In response to the raid, a high ranking Pakistani General issued a rare, pointed denunciation to the U.S. and stated that Pakistan's sovereignty would be protected "at all costs."[65] The UAV's combination of intelligence gathering, offensive firepower, and an ability to maintain a low profile represented the perfect answer for exploiting the intelligence gap that Greg Miller described, as a drone could identify militant leaders and kill them before they had changed hiding places. Thus, the CIA established its drone operation headquarters at Camp Chapman, located in the Khost region of Afghanistan. They incorporated their own assets at this location, including CIA operatives and local intelligence agents from Afghanistan and Pakistan.[66] To help identify militant leaders, the CIA made a secret agreement with Pakistan that facilitated intelligence sharing and allowed the UAVs to operate in the airspace above the tribal regions as long as the U.S. struck militant targets whose elimination mutually benefited the U.S. and Pakistan.[67] The CIA does not publicly acknowledge the drone program's existence because it would embarrass Pakistan by revealing their compliance in opening Pakistani air space to U.S. UAVs, but well-respected journalist Peter Bergen recently noted that the drone operation "is one of the worst kept secrets in history."[68]

By June 2004, Nek Mohammed had become a high profile target on the CIA's hit list.[69] An up-and-coming terrorist with overt connections to Osama Bin Laden, Mohammed represented the intersection of many different terrorist groups, including the Taliban and al Qaeda. The CIA tracked Mohammed to the remote Pakistani tribal regions and learned that Mohammed would be hosting a meeting with fellow militants on June 18th, 2004. The meeting's purpose was to reaffirm his devotion to waging Jihad against the U.S. During the meeting, he placed a satellite

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[64] Bergen and Tiedemann, 2010
[65] *Ibid.*
[66] Shultz, *op. cit.*
[67] *Ibid.*
[68] *Ibid.*
[69] *Ibid.*

phone call to a journalist to announce his position to the world – a call which was intercepted and tracked by a roving UAV. After Mohammed's identity was confirmed using voice analysis, the UAV fired a Hellfire missile at his house and killed Mohammed. The strike represented one of the first success stories for the newly formed drone program.

On January 13th, 2006, the CIA received intelligence indicating that a meeting of high level terrorists was occurring in a Pakistani village with an al Qaeda operations chief, a chemical weapons expert, and al Qaeda second in command Al Zawahiri all reported to be in attendance.[70] A UAV was dispatched, and it successfully destroyed the target location, reportedly killing everyone inside. Two weeks later, the CIA learned that it had struck the wrong house, killing 18 civilians, including several children. The mistake caused outrage across Pakistan, inflaming strong anti-American sentiment, and is possibly the single biggest event contributing to the perception that UAV strikes in Pakistan tend to kill scores of civilians. The fallout was so great that the CIA suspended all drone strikes for 9 months. However, the drone program was ultimately reinstated because drones represented the only possible means for striking targets in the Pakistani tribal region.

To improve strike accuracy, the CIA has reportedly paid locals to plant small electronic homing beacons by houses sheltering al Qaeda militants.[71] UAVs can track these beacons and strike the correct targets. This tactic has had a surprisingly effective psychological impact on al Qaeda operatives, who occasionally execute people they suspect of planting these devices out of fear and mistrust. UAV targeting also improved in 2009 after a renowned al Qaeda sympathizer, known as Balawi, was arrested in Jordan for posting extreme anti-American rants on a blog. Shortly

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[70] *Ibid.*
[71] *Ibid.*

after his arrest, Jordanian and CIA intelligence officials believed that Balawi's allegiance could be changed, thus making Balawi a useful CIA mole due to his credibility within Jihadi circles. After reportedly accepting a CIA deal that would make him a millionaire, Balawi was dispatched to the Pakistani tribal area to establish contact with high level al Qaeda militants and pass their targeting information to the CIA for use in UAV strikes. His intelligence served as the basis for many successful strikes. Saleh al-Somali, al Qaeda's external operations chief and Baitullah Mehsud, the leader of the Pakistani Taliban, were successfully targeted by a UAV during this time period.[72, 73] The latter strike may have potentially been the catalyst that ultimately compelled Balawi to betray his CIA handlers by detonating a suicide vest at Camp Chapman in December, 2009, killing seven CIA officers.[74] This double cross resulted in the single-biggest blow against the CIA in the War on Terror.[75] An unprecedented 13 drone strikes occurred during the three weeks immediately following Balawi's attack, causing experts to speculate that these actions were retaliatory.[76]

In the 2010 time frame, the CIA was focused on finding Mullah Baradar, the man who helped Taliban leader Mullah Omar flee Afghanistan in 2001.[77] Baradar was an experienced military commander who was directing the insurgent campaign against U.S. forces from the safety of Pakistan. Specifically, Baradar was responsible for the insurgency's increasing reliance on roadside improvised explosives. By 2010, Baradar had fled the Pakistani tribal areas to avoid UAV strikes. However, on February 10th, 2010, the CIA learned through intercepted phone calls that Baradar was possibly attending a terror meeting in the densely populated city of Karachi. At the CIA's request, Pakistani security forces raided the meeting and arrested Baradar. A similar

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[72] *Ibid.*
[73] Bergen and Tiedemann, *op. cit.*
[74] Shultz, *op. cit.*
[75] *Ibid.*
[76] Bergen and Tiedemann, *op. cit.*
[77] Shultz, *op. cit.*

situation unfolded on September 5th, 2011, when al Qaeda external operations leader Younis al Mauritania was arrested in the suburbs of Quetta, Pakistan.[78] Baradar and Mauritania's arrests in Pakistani cities demonstrated that the drone program's psychological influence on al Qaeda leadership forced them to relocate to areas where law enforcement officials have the resources to make arrests.[79]

In 2011, UAVs were increasingly involved in successful lethal operations targeting senior al Qaeda leaders. The Pakistani compound concealing al Qaeda mastermind Osama bin Laden was reportedly under surveillance by a drone with sophisticated stealth technology.[80] Such intelligence helped convince President Obama to send a Navy SEAL team to kill bin Laden in May 2011. One month later, Ilyas Kashmiri, one of Pakistan's most wanted militants, was reportedly killed in a June 2011 drone strike.[81] As recently as September 15th, 2011, Abu Hafs al-Shari, al Qaeda's chief of operations in Pakistan, was reportedly killed in a drone strike.[82]

Despite errant drone strikes in which many civilians were killed shortly after the drone program's creation, better intelligence has clearly increased the program's effectiveness over time by decreasing accidental civilian deaths and killing al Qaeda leaders at a rapidly increasing rate. Only two weeks after Baradar's capture, the New America Foundation published a policy paper stating that 114 drone strikes had been reported in the northwestern Pakistani tribal region since 2004, resulting in 830 to 1210 deaths.[83] Of those killed, an estimated 550 to 830 were believed to be militants, thus indicating that the true civilian fatality rate since 2004 was roughly 32 percent.

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[78] "Top al Qaeda leader arrested in Pakistan", 2011
[79] Shultz, *op. cit.*
[80] Bumiller and Shanker, *op. cit.*
[81] *Ibid.*
[82] Levine, 2011
[83] Bergen and Tiedemann, *op. cit.*

Civilian deaths, even if unintentional, are an important factor when analyzing the drone program's effectiveness because they are a politically charged issue in Pakistan. Pakistani citizens are overwhelmingly opposed to the drone program, in large part due to the perception that the strikes recklessly kill civilians and violate the nation's sovereignty. Indeed, an August 2009 Gallup poll revealed that only 9 percent of Pakistanis approved of such attacks.[84]

However, the New America Foundation's report noted that the 2009 average civilian fatality rate was only 24 percent, which was significantly lower than the aggregate rate of 32 percent. When examining the data collected through August 28th, 2011, the 2010 average civilian fatality rate had fallen even further to 5 percent, and the total aggregate civilian fatality rate decreased to 20 percent. These sharp reductions in civilian fatalities are a testament to the CIA's increased intelligence-gathering capabilities to avoid mistaken targets, and the precision of UAV technology and operations.

As the civilian death rate was declining throughout the decade, the frequency of drone strikes was rapidly increasing. After president Obama was inaugurated in January, 2009, the number of drone strikes skyrocketed. For example, 51 strikes were reported in 2009 alone, which killed as many as 10 militant leaders.[85] By comparison, only 45 strikes occurred during the entire Bush administration.[86] Drone strikes during the Obama administration are also killing al Qaeda leaders with increasing frequency. As of June 2010, drone strikes had killed at least 13 militant leaders since Obama took office in January 2009, a rate that far eclipsed the 16 militant leaders that were killed during the five years that President Bush authorized drone strikes in Pakistan. Indeed, this

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[84] *Ibid.*
[85] *Ibid.*
[86] *Ibid.*

figure is already dated, as al Qaeda's most recent second in command was killed in a drone strike on August 22nd, 2011.[87] Overall, four different militants who held the third highest leadership position within al Qaeda have been killed by drone strikes since 2001.[88]

The escalation of drone strike frequency in 2008 was initially accompanied by record violence in Afghanistan and Pakistan in 2009, causing some experts to speculate that the CIA's drone program was ineffective in disrupting terrorist plots.[89] Bruce Hoffman, a Georgetown University expert on terrorism, noted that the drone program's failure to reduce violence resembled the deteriorating security environment in Iraq following Abu Musab al-Zarqawi's death during a 2006 airstrike, implying that airstrikes were ineffective in dealing with a violent insurgency. Extending this principle to the CIA's drone program, drone strikes against militant foot soldiers may not seriously impact the overall number of militants and potentially increases their ability to recruit locals enraged by civilian deaths.[90] However, some experts also speculated that the increase of violence in Pakistani cities was a result of militants fleeing from drone strikes in the tribal areas, as was demonstrated by the recent high level captures of two al Qaeda leaders outlined earlier.[91]

However, these criticisms appear shortsighted when considering the overall impact of drone strikes in Pakistan. Although violence reached record levels in Afghanistan and Pakistan in 2009, it was mainly confined within these countries. The recent trend of decreasing civilian casualties resulting from drone strikes has likely decreased any positive impact that such strikes have had on

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[87] Miller and Tate, 2011
[88] Bergen and Tiedemann, *op. cit.*
[89] *Ibid.*
[90] Shultz, *op. cit.*
[91] Bergen and Tiedemann, *op. cit.*

militant recruiting. Additionally, al Qaeda militant leaders seeking refuge in Pakistani cities are starting to be arrested by local authorities.

Indeed, the recent increase in the number of militant leaders targeted in drone strikes suggests that the UAV's capabilities have been successfully tailored to meet a specific U.S. *strategic* goal. In contrast to the CIA's UAV usage, the U.S. military had been ineffectively using UAVs to serve purely tactical goals, such as spotting improvised explosives and ambushes, thus providing the perception that the U.S. military's UAVs were not having any useful impact in the War on Terror. In a March 2011 report titled, "Fixing Intel: A Blueprint for Making Intelligence Relevant in Afghanistan," Maj. Gen. Michael T. Flynn, the Army's top intelligence officer in Afghanistan, offered this analysis regarding why the U.S. military's purely tactical use of drones had not effectively improved the long term security environment in Afghanistan: "Aerial drones and other collection assets are tasked with scanning the countryside around the clock in the hope of spotting insurgents burying bombs or setting up ambushes. Again, these are fundamentally worthy objectives, but relying on them exclusively baits intelligence shops into reacting to enemy tactics at the expense of finding ways to strike at the very heart of the insurgency. These labor-intensive efforts, employed in isolation, fail to advance the war strategy and, as a result, expose more troops to danger over the long run."[92] Flynn's comments highlighted how overreliance on UAV ISR capabilities could actually prolong militant violence by failing to couple the effort to an over-arching wartime strategy, such as the CIA's effort to proactively hunt and eliminate al Qaeda's leadership structures.

[92] Flynn, Pottinger, and Batchelor, 2010

According to Col. John Warden III, targeting an enemy's leadership structure is the best strategic action that maximizes the impairment of enemy capabilities and minimizes the costs associated with the action.[93] Instead of focusing its efforts on the limitless supply of militant fighters, the CIA has used its drones to target al Qaeda's chief facilitators that possessed a unique combination of global connections among various militant groups, local support, and access to financial resources and technical knowledge. The reduction in attacks on Western targets during the 2009 violence in Afghanistan and Pakistan corroborate the importance of these "facilitators" to al Qaeda's mission to attack the West, as the terrorist group has had greater difficulty in directing its vast numbers of local fighters in its global terror campaign. Additionally, the psychological impact caused by the drone strikes further exacerbates the militants' logistical problems. David Rohde, a New York Times reporter who was held for seven months by the Taliban-allied Haqqani network, described the drones as "a terrifying presence" in the Pakistani tribal region of South Waziristan, causing militant leaders to sleep outside under trees to avoid being struck.[94] Taliban militants also routinely execute locals suspected of passing targeting information to the CIA. Several European militants captured in late 2008 "described an atmosphere of fear and distrust among members of al Qaeda in Pakistan," and a Tunisian-Belgian militant emailed his wife telling her that he had nearly been killed in a drone strike.[95]

As trusted, well-connected militant leaders are increasingly killed by drones, the resulting culture of paranoia threatens to drive various terrorist networks even farther apart, thus compounding al Qaeda's ability to operate globally. As recently as August, 2011, newly-appointed Defense Secretary Leon Panetta noted that "al-Qaida's defeat was within reach if the U.S. could mount a

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[93] Warden III, 2011
[94] Bergen and Tiedemann, *op. cit.*
[95] *Ibid.*

string of successful attacks on the group's weakened leadership."[96] Because he was Director of Central Intelligence during the height of the CIA's drone program in Pakistan, Panetta's statement indicates that the U.S. recognizes the UAV's new-found strategic value against al Qaeda leadership and will likely continue to use the drones in this capacity for the foreseeable future. In September 2011, the Under Secretary for Defense Intelligence recently said that "[al Qaeda's] senior leaders are being eliminated at a rate far faster than al Qaeda can replace them, and the leadership replacements the group is able to field are much less experienced and credible."[97] He further stated that "[we] have substantially attrited [al Qaeda's] mid-level operatives, trainers, and facilitators, its recent recruits, including westerners, and senior leaders and operatives of its safe haven providers," predicting that the fallout could destroy al Qaeda within the next two years.[98] In 2011 alone, al Qaeda has lost nine of its twenty-most senior leaders from 2001, with only one remaining.[99] Current CIA director David Petraeus observed that such catastrophic losses could force al Qaeda members to abandon Pakistan for other safe havens.[100] However, White House counterterrorism adviser John Brennan recently reaffirmed the U.S.'s commitment to the drone strategy targeting militants, noting that the administration would not rule out future unilateral strikes, even in allied territories.[101] Such a bold statement suggests that the U.S. will continue to employ UAV technology to target al Qaeda militants no matter where they flee.

In short, because UAVs allow the U.S. to project casualty-free military power into countries in which manned elements cannot be easily deployed, UAVs have been instrumental in weakening al Qaeda's organizational capabilities by targeting its key leadership elements taking shelter in

[96]Apuzzo, 2011
[97] Levine, *op. cit.*
[98] *Ibid.*
[99] *Ibid.*
[100] *Ibid.*
[101] Cratty, 2011

Pakistan's Federally Administered Tribal Areas' rugged, remote terrain. Consequently, the CIA's effective use of UAVs to serve *strategic* goals is a model ready to be adopted and expanded by the U.S. Air Force to increase its relevance in the War on Terror.

1.3 **Current and Imminent UAVs Advantages**

Before exploring the advantages and technological inroads associated with autonomous UAVs of the future, current tactical and logistical advantages provided by UAVs will be briefly discussed. Such advantages are numerous and may presage the replacement of virtually every aircraft in use today. Indeed, one U.S. Air Force engineer noted that “you can envision unmanned systems doing just about any mission we do today.”[102] However, only select UAV advantages will be discussed here, while additional advantages provided by future autonomous systems will be specifically addressed later.

As previously explained, a UAV’s most visible advantage is that it allows nations to project power without risking casualties because these vehicles contain no human operators onboard. By serving as proxies for human soldiers, UAVs allow human operators to prosecute a war effort from the safe confines of military bases many thousands of miles away. This characteristic is extremely valuable in combating counterinsurgencies because it prevents militants from achieving their main objective: kill enough occupiers that they lose the political will to continue the fight. Additionally, the lack of onboard operators allows UAVs to be used in politically sensitive areas in which the deployment of human soldiers would create too much controversy. Such is the Pakistan situation described above, where UAVs have been used with great success to eliminate Al Qaeda leadership.

UAV technology provides numerous other current and imminent advantages to military and intelligence planners. For example, UAVs can accelerate and maneuver beyond the limits

[102] Austen, *op. cit.*

permitted by human biology.[103] Without such human constraints, UAVs can be designed to accomplish missions in manner that was never previously possible using manned aircraft. For example, as recently as August 2011, the Defense Advanced Research Projects Agency (DARPA) launched an experimental unmanned aircraft that traveled at 20-times the speed of sound.[104] Such a feat was enabled by the development of a scramjet that captures oxygen for combustion directly from the air. Such technology would enable UAVs to use significantly less fuel, thus reducing their weight and allowing them to carry more payloads.[105] Alternatively, reduced weight combined with supersonic speed could allow UAVs to be launched into space.[106] Given the U.S. Air Force's recently launched unmanned X-37B space plane and research on radioisotope-powered UAV engines for use in oxygen-free areas, the lack of human engineering constraints may ultimately allow the development of space-based UAVs that can be deployed anywhere in the world with only a few hours' notice.[107,108] In fact, the U.S. Air Force's long term planning includes deploying hypersonic UAVs that can arrive anywhere on Earth in under 2-to-3 hours to conduct attack and/or ISR missions.[109, 110] Emerging high value, time-sensitive targets could be quickly monitored and neutralized by a hypersonic UAV regardless of geographic location, as hypersonic speed and access to outer space would reduce the need for forward air strips outside of the continental U.S.

In addition to designs that are not constrained by biological limits, current computerized weapon systems simply outperform humans in a number of tactical situations. Robots can perceive the environment and make decisions – albeit in a limited capacity – in ways and at speeds greatly

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[103] *Ibid.*
[104] Belfiore, 2011.
[105] *Ibid.*
[106] *Ibid.*
[107] Factsheets: X-37B Orbital Test Vehicle Fact Sheet, 2011
[108] See http://www.usra.edu/cs/isotope_power_for_unnamed_aerial_vehicles
[109] Magnuson, 2010 (Spate of Hypersonic Vehicle Tests Fuels Global Strike Debate)
[110] Magnuson, 2010 (Next Generation: Future Remotely Piloted Aircraft Will Do More Than Surveillance)

surpassing humans.[111] Differences in processing speed are a product of physical differences: a human's nervous system is relatively slow because it is limited by slower chemical transmission within synapses, whereas a robot's "nervous system" is strictly governed by near speed-of-light electronic signal transmission. Differences in perceptual capabilities exist because robots can detect and manipulate stimuli in ways that the human brain is not equipped to handle. For example, robots can use acoustic technology to instantly pinpoint the location of a sniper who has just fired.[112] Such perceptual ability could allow a robot to instantly return fire against well-hidden targets. Some military robots can already precisely fire high-energy lasers, hitting targets far more accurately than humans.[113] Counter Rocket, Artillery and Mortar (C-RAM) systems currently protect the Green Zone in Iraq by using radar to automatically detect and neutralize incoming ordinance with a Gatling gun.[114] This system successfully intercepts incoming projectiles 70% of the time.[115]

The absence of human operators affords UAVs deployment longevity advantages, as well. Advances in solar technology will enable future UAVs to loiter in outer space and power UAV flight within the atmosphere for extended periods. In 2010, Qinetiq's Zephyr UAV successfully remained airborne for 14 days using solar technology, and its developers now believe that the technology is capable of sustaining year-round flight within 40 degrees of the equator.[116] Indeed, DARPA is currently interested in developing solar powered UAVs that can stay airborne in one region for 5 years at a time.[117] These UAVs would provide continuous ISR capabilities in areas

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[111] "Remote Control War", *op. cit.*
[112] "Remote Control War", *op. cit.*
[113] Austen, *op. cit.*
[114] *Ibid.*
[115] *Ibid.*
[116] Sweetman, 2010.
http://www.aviationweek.com/aw/generic/story_channel.jsp?channel=defense&id=news/dti/2010/10/01/DT_10_01_2010_p53-256010.xml&headline=Drone-Specific%20Technologies%20Emerge
[117] "High-Altitude Aircraft Could Spy for 5 Years Nonstop," 2011.

that are difficult to penetrate in a cost-effective manner.[118] Such persistence would also allow these UAVs to serve as geostationary communication relays that are 1,800 times closer to user earth stations than current geosynchronous satellites, thus allowing the earth terminals to be much smaller and harder to detect.[119]

Tactical considerations aside, UAVs serving as reliable communication relay hubs allow other UAVs to be remotely piloted without the need for expensive satellites, thus significantly reducing economic costs associated with any UAV operation. UAVs regularly consume large amounts of bandwidth to send video feed and sensor data to remote operators and intelligence analysts.[120] Consequently, competing demands for continuous wideband access are overloading available satellite capacity.[121] After canceling the Transformational Satellite program which would have provided additional satellite capacity, the Air Force has increasingly turned to commercial providers for additional capacity.[122] The private sector now provides a staggering 80 percent of the U.S. Air Force's bandwidth needs.[123] Commercial satellites are not as secure as military satellites, thus leaving UAVs vulnerable to cyber-attacks that may render them both helpless and useless.[124] Additionally, commercial satellites sometimes operate at frequencies that are incompatible with UAV needs.[125]

Because launching satellites is becoming more expensive and because the Department of Defense is expected to see decreasing budgets in the near future, the U.S. Air Force will not likely meet its

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118 *Ibid.*
119 *Ibid.*
120 Jean, 2011
121 *Ibid.*
122 *Ibid.*
123 *Ibid.*
124 *Ibid.*
125 *Ibid.*

own bandwidth demands during the next few decades.[126] Thus, deploying covert UAV satellite surrogates will reduce the U.S. Air Force's reliance on technologically vulnerable commercial satellites without the expense of developing and deploying new satellites. Additionally, reducing the military's "footprint" on commercial satellites has societal benefits, as these satellites would likely no longer be considered valid targets in wars fought among technologically advanced states.

UAVs whose energy demands cannot be fully met by solar technology can be continuously refueled by other UAVs that can perform midair fueling.[127] For the past 60 years, the U.S. Air Force has used manned planes to refuel nuclear-armed bombers so they could be ready to strike at a moment's notice.[128] Such midair refueling operations requires delicate precision, as a small mistake could damage both aircraft involved in the maneuver. Because of their rapid abilities to accurately sense and adjust, autonomous systems excel at such tasks, thus making them ideal for this role. Similar to the advantages afforded by scramjets, aerial refueling allows individual UAVs to travel farther and reduces their weight.[129] Extended operational ranges allow a smaller number of UAVs to handle global mission requirements, and reduced weight allows UAVs to take off from shorter runways and carry larger payloads.[130]

UAVs are also primed to take over transportation and logistical roles. For example, UAVs could be used to regularly resupply U.S. military bases.[131] This role would be extremely useful for remote outposts, such as those maintained by the U.S. military in eastern Afghanistan, where

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[126] *Ibid.*
[127] Austen, *op. cit.*
[128] *Ibid.*
[129] *Ibid.*
[130] *Ibid.*
[131] Magnuson, *op. cit.*

rough terrain and hostile insurgents greatly hinder resupply missions using freight trucks originating in Pakistan. Such trucks are frequently attacked en route to the outposts, and the danger always exists that the local drivers could actually be suicide bombers attempting to penetrate the outpost's perimeter defenses. By flying supplies into the outposts using UAVs, willing drivers need not be found, ground supply vehicles will not be exposed to IED threats, suicide bombers would be unable to infiltrate outposts, and Pakistan would have less ability to impede resupply missions through its territory, thus giving it less political leverage over the U.S. Additionally, no U.S. pilots would be at risk flying routine resupply missions. Helicopter UAVs are seen as an ideal cargo-transporting UAV, which would preclude the need for good weather and constructing sophisticated air strips at these rugged outposts.[132, 133]

Additionally, transport UAVs could eventually shuttle special operations soldiers to the high value targets, such as militant leader enclaves. Because the success of any militancy strongly relies on secrecy, such individuals frequently hide in remote, rugged terrain, or among dense urban environments ruled by governments that sympathize with their causes.[134] To covertly and quickly penetrate these areas, special operations soldiers will frequently travel by air in the middle of the night. Transport pilots will often fly without lights to avoid visual detection, and they frequently fly at very low altitudes to avoid radar detection. Such was the situation when special operation forces killed Osama bin Laden in May, 2011.[135] Operating aircraft in such challenging situations with reduced sensory input is risky, increasing the attractiveness of inserting UAV technology into such missions. Indeed, relying on infrared and radar technology,

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[132] Lendon, 2010
[133] Hatamoto, 2012
[134] Rath, 2011
[135] Schmidle, 2011

UAVs can already autonomously fly and land in harsh conditions, such as Iraqi sandstorms, that challenge even the best human pilots.[136]

By 2015, sense-and-avoid technology should allow UAVs to detect other airborne objects and avoid them.[137] At present, technology is available to automatically steer manned aircraft away from the ground when an imminent collision is detected.[138] This system could easily be installed on UAVs, thus increasing their safety during low altitude, night time flying. Additionally, most manned aircraft already heavily rely on autopilot capabilities, which resemble the same technology used to guide UAV decision-making processes. UAV technology would essentially enhance this autopilot capability by allowing the aircraft to dynamically choose flight trajectories that maximize fuel efficiency, thus allowing the UAVs to carry less fuel.[139] Reducing the UAV's weight by removing human pilots and decreasing fuel capacity may allow each individual craft to carry more soldiers and equipment, thus potentially allowing fewer aircraft to be used on risky insertion operations. This issue was very important during the raid that successfully targeted Osama bin Laden, as each aircraft was loaded to the platforms' maximum weight capacities.[140] Excess weight is thought to have contributed to a stealth helicopter's crash during that mission.

The heretofore discussed UAV advantages can be achieved on current non-autonomous UAV platforms. *Autonomous* UAVs – those that contain some capacity to sense the environment and make tactical decisions without human input – provide quantum improvements over the significant technology benefits just described. Before considering these it is important provide

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[136] Schneider, *op. cit.*
[137] Austen, *op. cit.*
[138] *Ibid.*
[139] *Ibid.*
[140] See http://defensesystems.com/articles/2011/05/05/agg-helicopter-crash-bin-laden-raid.aspx

balance to the discussion by addressing the potential problems posed by increased reliance on UAV technology in warfighting.

1.4 **Challenges of UAV Usage**

So far, the discussion has been largely affirmative, focusing on the UAV's history and advantages. Despite their many advantages, UAVs remain somewhat controversial. Before specifically examining future prospects for UAV autonomy, select challenges will first be explored to provide a broad context of the other issues associated with their use. Many of these issues will not be resolved by increasing UAV autonomy, and thus any final analysis regarding the usefulness of autonomous UAVs must weigh both the advantages and disadvantages.

Although UAVs are perceived to save the lives of the humans that they replace in battle, their use may provide conditions that undermine their effectiveness by creating an environment that promotes human casualties for the following seven reasons:

(1) UAV use causes society to become increasingly disconnected from war initiation decisions and from ongoing war efforts because it perceives warfare's cost to be significantly smaller than in the past.

(2) UAV use contributes to leadership structures becoming increasingly overconfident with regards to technological advantage and, consequently, lower the threshold for conflict initiation.

(3) The distance of UAV "combatants" from lethal engagements makes it easier for humans to kill other humans.

(4) The state of legal accountability regarding robotic actions is currently unclear, leading to few repercussions when atrocities are committed using UAVs.

(5) UAV-specific technical vulnerabilities could be exploited to reduce UAV effectiveness or, at worst, make UAV employment a liability. Specifically, if UAVs become ineffective due to these vulnerabilities, the U.S. may find itself in a war that it is suddenly not prepared to fight. Additionally, malfunctioning UAVs could engender conflicts that the U.S. did not intent to initiate. In rare instances, compromised U.S. UAVs could potentially be used against the U.S.

(6) Increased UAV usage could increase terrorist recruiting by galvanizing foreign citizens who view drone strikes to be a violation of their nation's sovereignty and a cowardly means of fighting. These six issues may combine to increase conflict frequency and duration, which could *potentially* lead to more total deaths around the world. While the use of drone technology has undoubtedly provided many advantages, the implications of this technology's usage must be carefully explored, as many human lives may be at stake.

(7) UAV technology proliferation will place civilian populations and infrastructure at risk from rogue nations and terrorist organizations.

1.4.1 **A Disconnected Public**

Immanuel Kant's 1795 essay *Perpetual Peace* states that democracies are inherently peaceful because the people ultimately have a say in decisions, and their collective decisions are wiser than a single dictator's.[141] Because dictators force others to fight, the threshold for waging war is low in a dictatorship. Conversely, whenever war occurs in a free society, the public chooses to bear the brunt of the fighting, pay for the war, repair the destruction, and potentially suffer tremendous national debt. Many capitalistic industries would also suffer if their infrastructure was destroyed in a protracted conflict. Consequently, the public and the business sectors will theoretically only support a war if the country is severely threatened and if no other recourse is available. Because the public is closely connected to warfare through potential personal losses of family, friends, and wealth, a free society will be intimately involved in participating in all discussions regarding war's initiation and cessation.

In recent years, society is becoming increasingly disconnected from discussions regarding the use of war to achieve desired objectives because its members perceive war's personal and national costs to be significantly smaller than in past wars. In general, war's human cost has significantly decreased over the past two decades when compared to earlier wars in the 20th century. Figure 1 displays American casualty figures in each major war over the past 100 years:

[141] Kant, 1795.

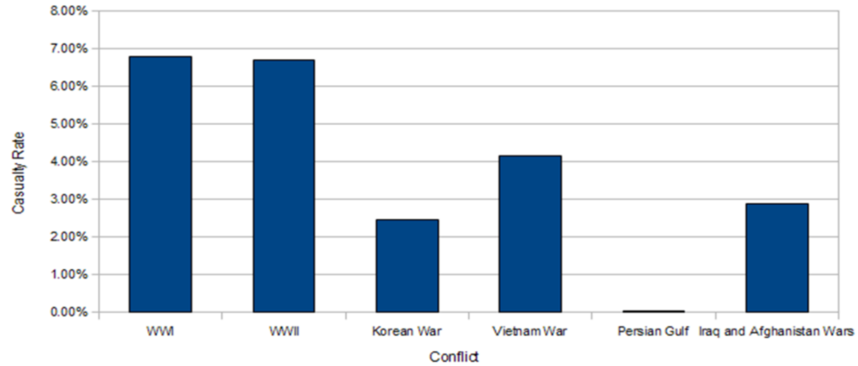

***Figure 1**: **Historical Casualty Rates for American Soldiers in Recent Wars** as a Percent of Total Number of Soldiers Serving in Each War. (Data acquired from InfoPlease. 2010; Leland and Oboroceanu, 2010)*

These data show a general trend of decreasing casualty rates over the past century. Contrasting the two largest extremes of American losses within the past century, an estimated 405,399 Americans died in World War II, whereas only 2 Americans died in the Kosovo War (not shown).[142, 143] Unlike World War II, Americans and their allies utilized their vast technological advantage to safely attack Serbian targets during the Kosovo War. In fact, the entire 11-week campaign was won based exclusively on aerial bombardments.[144] Additionally, the following chart documents the number of U.S. servicemen who served in each of these wars:

[142] Leland and Oboroceanu, 2010
[143] “Two die in Apache crash”, 1999
[144] Sturgeon, pg. 347, *op. cit.*

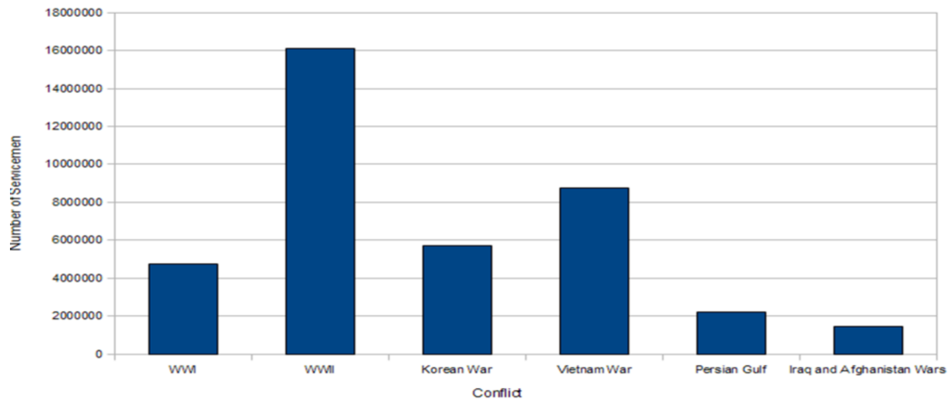

***Figure 2**: **Number of U.S. Servicemen Serving in Each War** (InfoPlease. 2010; Leland and Oboroceanu, 2010)*

These data suggest that the number of U.S. servicemen required to fight in major wars has been generally decreasing over the past century, particularly over the past twenty years. The reliance on superior military technology to quickly win wars and distance soldiers from danger undoubtedly spared American lives and has generally reduced the number of soldiers required to fight in war.[145] Unfortunately, this recent reality threatens to marginalize public concerns about warfare back home. Previous wars featured friends, family, and neighbors whose service placed them in danger, but because few Americans were ever realistically exposed to battlefield dangers in the Kosovo War, the public's "stake" in the war was decreased.

Similar to the impact of air power's distancing effect in war, the newest technological revolution of military robotic platforms engenders the ultimate disconnect between the public's interest and the decision-making process underlying future war discussions. Robotic systems allow human controllers to fight far away from the battlefield, thus reducing their otherwise small risk of combat-related death to near zero. In the Vietnam War, aircraft pilots were exposed to considerable risk when flying missions over the battlefield and some contracted deadly diseases

[145] Singer, *op. cit.*, pg. 398.

from the unsanitary, tropical squalor in which they resided.[146] Today, pilots located at Creech Air Force Base in Nevada can now remotely pilot UAVs to bomb targets located 7,000 miles away.[147, 148] One of the greatest dangers these pilots face during war are traffic accidents while commuting to and from work. Thus, the newest generation of servicemen and women are able to fight anywhere in the world while enjoying all the comforts that modern amenities can provide after working hours.[149]

While military members should be afforded the opportunity to live in comfort if the situation permits, today's situation threatens to reduce war's negative psychological consequences for the soldiers and their families because both groups will be so distanced from war's horrors. For example, soldiers will not be in danger and will not experience the visceral emotions associated with physical presence at a battle filled with danger, death, and destruction. Families will neither experience the constant fear of losing a loved-one nor will they experience the sadness of missing a loved-one who is fighting in a distant land. The reduction of war's negative consequences ultimately threatens to disengage the public from war decisions, thus greatly reducing the likelihood of public veto of elected officials' war propensities.[150] The public is less likely to oppose a war they perceive to be costless, enabling the government to wage war unchecked, and thus potentially increasing the loss of life from involvement in unnecessary warfare.[151]

The public's decreasingly shared participation in war is not a new phenomenon but a continuing trend over the past 70 years. During World War II, the United States instituted conscription,

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[146] Harrison, 1989.
[147] Stone, 2010.
[148] Factsheets: Creech Airforce Base.
[149] Stone, *op. cit.*
[150] Kahn, 1999.
[151] Singer, *op. cit.*, pg. 323.

rationing of petroleum and rubber to civilians, sold war bonds to the public to finance the war, and issued a Congressional declaration of war. Today the United States fields a completely voluntary army, the public no longer buys war bonds, the government does not ration food or gas, and Congress has not issued a declaration of war since 1941.[152] This removal of the public's shared wartime sacrifices has already decreased the public's motivation to participate in war discussions. The introduction of robotic weapons might sever the final links that maintain the public's engagement, as even the soldiers' sacrifices are being diminished.

Economically, the robotic weapons themselves are far cheaper than manned vehicles. For example, one Predator UAV costs a mere $4.5 million, whereas the amount of money needed to purchase a single F-22 manned jet could purchase eighty-five Predator UAVs.[153] Similarly, the development of the F-35, the newest manned fighter jet, cost over twenty-two times as much to develop as the X-45, a revolutionary air combat UAV with state-of-the-art artificial intelligence.[154]

Because these UAVs record live video feeds of all combat situations, their widespread usage may provide countless hours of video combat feed to anyone with an internet connection. These feeds risk presenting war as an entertaining, ESPN-like experience where the general public can comfortably enjoy watching combat situations at home. Searching youtube.com with the term “UAV footage” yielded 2,030 results, and one of the first videos returned was labeled, “(Funny UAV Footage)”.[155] Additionally these videos likely do not include footage of American deaths,

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152 *Ibid.*, pg. 319.
153 *Ibid.*, pg. 33.
154 *Ibid.*, pg. 119.
155 youtube.com, 2010.

as such videos are frequently banned from U.S.-based home sites.[156] This biased perspective misrepresents war and, combined with decreasing human sacrifices and fewer tax-dollars needed to purchase cheaper robotic vehicles, could compel a society to take war less seriously, thus leading to increasing reliance on warfare to achieve political gains and, ultimately, to more deaths.

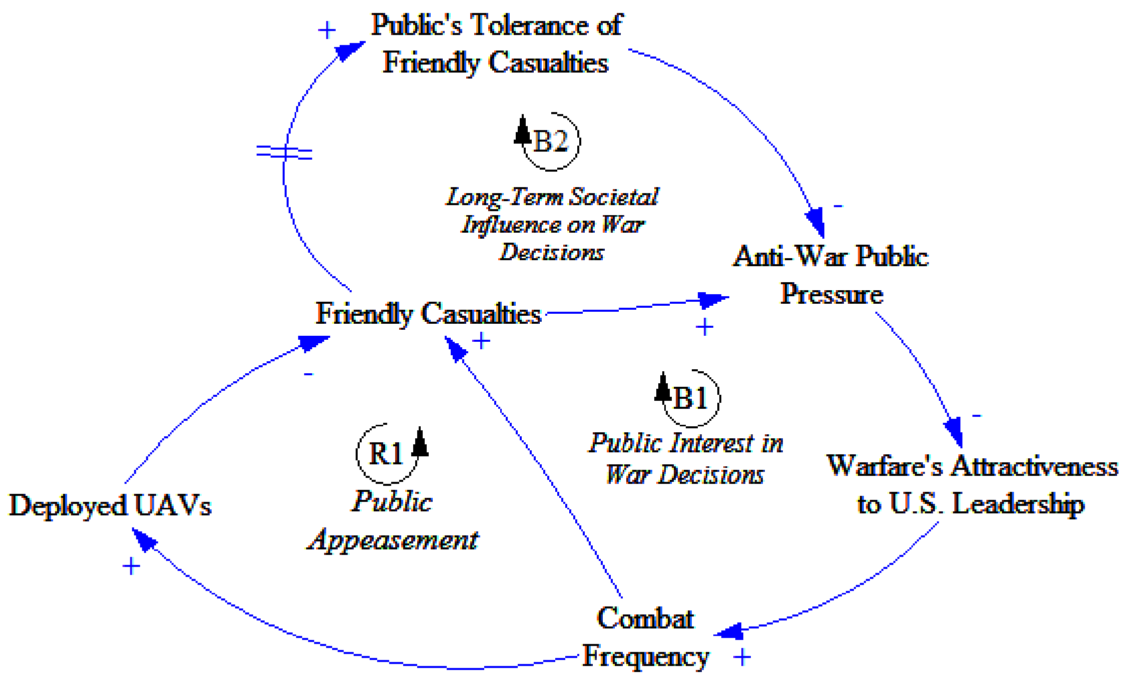

***Figure 3**: **Dynamics of UAV Usage and Public Pressure:** This figure contains causal loop diagram outlining both UAV and public pressure influences on conflict initiation. B1 represents the pre-existing balancing feedback loop in which the public pressures its leaders to avoid conflicts because of mounting friendly casualties. B2 represents a delayed balancing feedback loop in which the public becomes slowly accustomed to a certain amount of friendly casualties, thus influencing how much pressure they place on their leaders to avoid conflicts. R1 represents a reinforcing feedback loop in which UAV usage reduces the number of friendly casualties in conflicts, thus causing the public to exert less influence on leaders to avoid conflicts.*

[156] Singer, *op. cit.*, pg. 321.

1.4.2 **Overconfident Leadership**

In addition to changing public perceptions of war, leadership structures may become increasingly overconfident regarding the military advantage they perceive to possess from procuring advanced robotic systems. Admittedly, robotic weaponry does potentially offer unique advantages. As mentioned earlier, robots remove humans from the immediate war zone to the extent that they are used.[157] Additionally, robots have more accurate targeting mechanisms, do not eat food or require sleep, do not get bored or distracted, do not panic when facing danger, and are immune to biological weapons and some chemical weapons. An additional example can be found when examining the UAV, as drone usage increases the "strike window" in which targets can be identified before they're overflown because, unlike manned planes, these robots can hover over targets while assessing a situation below.[158]

The exponential growth of technological advances is providing increasingly powerful capabilities to military planners. Unfortunately, this rapid technological expansion may not always be good for humanity. The less-frequently discussed issue is the concomitant shrinking amount of time that humans have to adapt to technological changes and understand their implications. Previous generations had years, if not decades, to absorb significant technological changes, whereas the present generation must digest even greater numbers of technologies on shorter time-frames.

The combination of accelerated advances in computer processing speed, artificial intelligence, and conventional military weapons may quickly lead to robotic weapons capable of unleashing destruction on a scale never seen before. Based on previous growth trends, the military will

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[157] Stone, *op. cit.*
[158] Singer, *op. cit.*, pg. 394.

likely obtain these weapons before they fully understand the consequences of their use. This lack of understanding will also be fueled by both the scientists and industries that pioneered their development and manufacture, as these professions often feel compelled to overstate the usefulness of technologies to obtain hyper-competitive research funding. Even worse, their fast development could fuel a "use it or lose it" mentality among military and political leaders, as such a perceived decisive advantage would be quickly lost to enemy nations if the advantage was not pressed immediately.[159] Combined with the increasing public disinvestment, these factors will instill overconfidence in the leadership structure regarding the abilities of their newly-acquired technologies, which could lead to disastrous miscalculations when deciding whether to enter a war and how to execute a war strategy.

Ominously, over the past several centuries, the countries that initially pioneered a revolutionary military technology rarely used it the most effectively compared to other opposing countries that cheaply caught up by mimicking the technology.[160] A prime example of such a scenario is the development of the tank. Although France and Britain pioneered this new military technology, Germany ultimately used it against them with great effectiveness during the Blitzkrieg.

Robotic technology is also likely to reshape war's nature itself. Previous policy decisions typically held military action as the option of last resort.[161] Being smitten with the advantages afforded by robotic weaponry, elected officials will likely continue selling "shock and awe" tactics to the general public, perpetuating the mistaken belief that war can simply be won by a large show of technological force, with the Kosovo War and the 2003 Iraq War being recent

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[159] "Nanotech Arms Race", 2004.
[160] Singer, *op. cit.*, pg. 239.
[161] Bacevich and Kaplan, 1996.

examples.[162] Future wars will likely resemble NATO's involvement in the Kosovo war, where a concerted effort was made to avoid committing ground forces to the war effort, as the existence of robotic platforms will likely raise the ante for human presence in battle.[163] Similarly, the cost of military action may become so low to a “UAV Power” that brief military strikes might become a frequent alternative to diplomacy, reminiscent of the cruise missile diplomacy of the 1990s.[164] Such short-term military action gives the illusion that an objective has been accomplished, but, in most cases little lasting gain is made from such actions and regrettably involves the perpetrating country in unnecessary armed conflict.

Occasionally, overconfidence in technology will lead to short-sighted war planning where overreliance on UAVs may lengthen armed conflicts despite the fact that their promise of casualty reduction could lower conflict thresholds.[165] Such protracted engagements may increase human loss of life, with the 2003 Iraq War and the 2001 Afghanistan War being two recent examples. Overreliance on UAV technology will likely reduce the number of “boots-on-the-ground” needed to end conflicts by occupying and securing the enemy’s territory. The existence of UAVs may make the public unwilling to sacrifice their loved ones if they perceive that an unmanned solution exists for combating enemy forces. Additionally, since personnel represent the largest cost to the U.S. military, manned forces may also be reduced as UAVs are increasingly purchased to reduce the Pentagon’s costs. Without enough soldiers to fully secure a geographic area, U.S. forces will be stretched thin, exposing them to danger and increasing the difficulty of locating and engaging enemy forces. Consequently, the U.S. may have difficulty *winning* the conflicts that it so easily initiated.

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[162] Singer, *op. cit.*, pg. 322.
[163] *Ibid.*, pg. 316.
[164] Gentry, 2002.
[165] Singer, *op. cit.*, pg. 322.

While new robotic technologies will certainly be capable assets, their rapid development and deployment will likely outpace a country's ability to fully understand and adapt to the consequences of their use. Despite this lack of complete understanding, a country's leadership may feel compelled to use this new-found advantage before other countries catch up.[166] This rush to exploit a fleeting advantage could cause both unnecessary warfare and war mismanagement, which in turn will lead to additional deaths from robots' use.

[166] "Nanotech Arms Race", *op. cit.*

1.4.3 **Polarization of Public Opinion**

Earlier analysis featured UAV successes from the U.S.'s perspective, but the U.S.'s increasing reliance on UAVs has also polarized U.S. public and, particularly, international opinion – regarding UAV usage. A recent poll showed strong domestic support for drones, with 9 out of 10 U.S. veterans and 68 percent of the general U.S. public indicating that they supported UAV usage.[167] According to a report by the Aryana Institute for Regional Research and Advocacy, drone strikes are generally supported by the public in Pakistan's Federally Administered Tribal Areas (FATA).[168] Based on hundreds of interviews from FATA residents, 52 percent considered the air strikes to be accurate, 58 percent felt that the strikes damaged the militants, and 70 percent felt that the Pakistani army should also target the militants.[169] Farhat Taj, a Pakistani academic, argued in 2010 that FATA's Pashtun residents embraced the UAV intervention when she noted that, "[the] people of Waziristan are suffering a brutal kind of occupation under the Taliban and al Qaeda. It is in this context that they would welcome anyone, Americans, Israelis, Indians or even the devil, to rid them of the Taliban and al Qaeda. Therefore, they welcome the drone attacks."[170] Additionally, Taj noted that, "the people feel comfortable with the drones because of their precision and targeted strikes. People usually appreciate drone attacks when they compare it with the Pakistan Army's attacks, which always result in collateral damage. Especially the people of Waziristan have been terrified by the use of long-range artillery and air strikes of the Pakistan Army and Air Force."[171] The statement implies that local FATA residents prefer UAV strikes to Pakistani military strikes because the operational consequences of UAV strikes are more

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[167] Basu, 2011
[168] Khan, 2011
[169] *Ibid.*
[170] Taj, 2010
[171] *Ibid.*

humanitarian for civilians. Thus, UAV usage appears to be accepted by both the U.S. public and the civilians in the region of conflict who are most directly affected by the strikes.

However, this sentiment is not shared in the other areas of Pakistan. Less than 10% of Pakistani citizens support American UAV drone strikes on Pakistani soil because they view the strikes as violating their national sovereignty, even though such strikes target militants that also threaten Pakistan's security.[172, 173, 174] Additionally, 67% of Pakistanis oppose the drone strikes.[175] Such displeasure was highlighted when a song mocking American cowardice because of its reliance on UAVs to strike Pakistani targets became popular in Pakistan.[176] Such a song reflects the possibility that instead of being terrified, militants may perceive UAV usage as a sign of America's fear of casualties, further emboldening terrorist activities.[177] Generally speaking, such a popular song indicates that foreign nationals do not welcome outside military interference in matters that are widely perceived to be internal affairs. Specifically, the average Pakistani worries that drone strikes will inflame militants and cause them to increase the rate of their suicide attacks against innocent civilians.[178] Some evidence exists to support this view. Violence spiked immediately following successful strikes on high profile militants, such as Abu Mus'ab al-Zarqawi in Iraq and Mek Muhammad and Baitullah Mehsud in Pakistan.[179] This observation was echoed by U.S. Army Major General Flynn when he noted that "…inescapable truth asserts that merely killing insurgents usually serves to multiply enemies rather than subtract them."[180] The

[172] Benson, 2010
[173] Bergen and Tiedemann, 2010
[174] Khan, *op. cit.*
[175] *Ibid.*
[176] Mazzetti, 2009
[177] Khan, *op. cit.*
[178] *Ibid.*
[179] *Ibid.*
[180] *Ibid.*

Soviet Union faced similar circumstances when the insurgency became larger as the war dragged on despite the many casualties that the Soviet Union had inflicted.[181]

Due to their widespread unpopularity in Pakistan, extreme outrage typically occurs when UAVs accidentally strike civilian targets, although such mistakes are becoming increasingly uncommon as intelligence-gathering practices improve. As was mentioned earlier, the 2004-2010 aggregate non-militant fatality rate associated with UAV strikes in Pakistan was 20% and the 2010 rate was 5%, indicating that targeting intelligence has become more precise. Regardless, such accidents are detrimental to America's war efforts because the United States' enemies will likely harness some subset of the resulting negative perception as propaganda to recruit additional fighters. Indeed, when UAV strikes accidentally kill women and children, Pashtun customs obligate the survivors to seek revenge, thus potentially offsetting the gains acquired from the strike.[182] Renowned journalist Rahimullah Yusufzai observed that drone strikes were compelling previously unaffiliated people to support the Taliban.[183] High profile Taliban leaders Baitullah Mehsud and Hakimullah Mehsud have used UAV unpopularity to increase the group's appeal to average Pakistanis and as a means to justify Taliban suicide attacks against a Pakistani government that is perceived as being complicit with the drone strikes.[184] Major General Flynn acknowledged this Taliban strategy when he noted that "[at] all times, however, the Taliban capitalize on the ensuing mayhem and gain new recruits and re-energize old ones."[185] Admittedly, this dynamic would likely be worse if manned aircraft had been used to strike militant targets, as these jets would additionally invoke the ire of the Pakistani government. Additionally, manned aircraft would also likely cause more collateral damage due to their

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181 *Ibid.*
182 Mezzetti, *op. cit.*
183 Khan, *op. cit.*
184 *Ibid.*
185 *Ibid.*

inability to perform a pattern-of-life analysis by monitoring a target for hours upon end coupled with a smaller window of opportunity to strike the target.

The key question is whether or not UAV usage is creating more militants than they are eliminating. Although no definitive answer can be provided, given Pakistan's large population and thus widespread potential for radicalization, the previous analysis suggests that the answer might be "yes." Additional enemy recruitment will further increase attack frequency, thus further escalating regional violence, thus causing even greater anti-American sentiments. Growing Taliban support throughout Pakistan could provide an environment that better facilitates Taliban organization and planning, thus allowing the group to engage in international violence.

The following Stock-and-Flow diagram in Figure 4 summarizes the dynamics outlined so far:

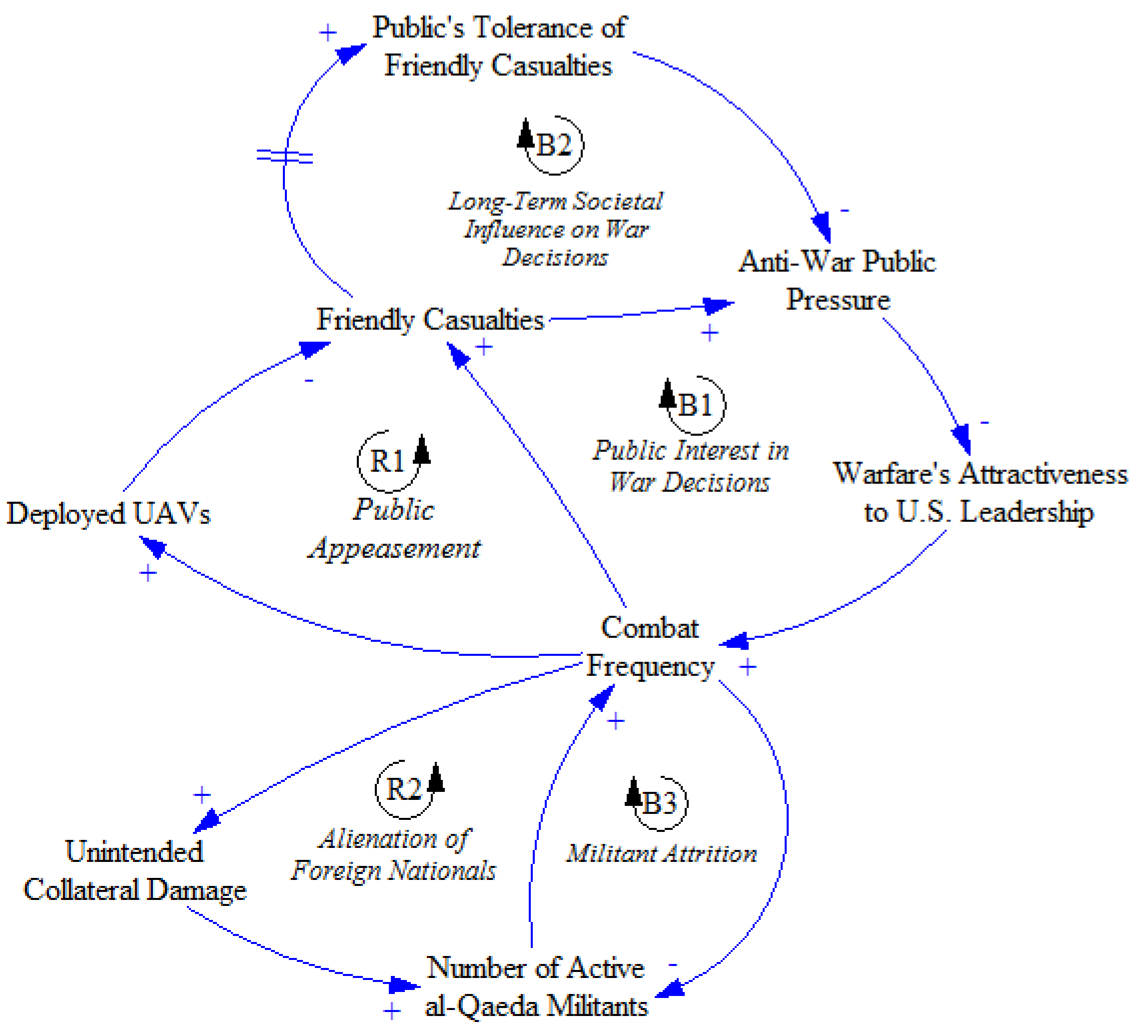

Figure 4: Dynamics of Foreign National Alienation and Militant Attrition: *This causal loop diagram represents Figure 3 with the additions of loops R2 and B3. The R2 loop indicates that militant groups will experience increasing recruitment success as collateral damage from combat increases. Consequently, a burgeoning militant group will expand its terrorist activities, further increasing combat frequency. The B3 loop simply indicates that the number of militants will decrease as they are killed in the increasing number of combat engagements.*

1.4.4 Technical Vulnerabilities

In addition to social and political risks surrounding drone usage in war, UAVs themselves have inherent technological vulnerabilities that an enemy could exploit to cause significant backlash on the user. Computer systems have long been susceptible to an array of attacks, all of which originate from distant, often ambiguous, sources. For example, software is susceptible to disruption via computer viruses that imbed themselves into executable files or from malicious worms that can operate completely on their own. Because UAVs are becoming increasingly dependent on computer-based artificial intelligence to carry out normal operational functioning, UAVs are becoming increasingly susceptible to these same types of attacks that have disrupted computer systems the past few decades.

October 2011 featured the first reported instance of a virus infecting classified computer systems used to control UAVs despite the fact that the computer systems were reportedly isolated from the internet.[186] The virus was a keystroke logger, which is a common type of malware that did not appear to be specifically designed to disrupt UAV operations. Prior to this incident, some experts were already expressing concerns about UAVs' technical vulnerabilities. For example, U.S. medical costs are compelling high-tech firms to outsource much of their manufacturing capacity to foreign countries, such as China and India, causing America's trade balance in high-tech goods and services to drop from plus $50 billion in 1996 to minus $50 billion in 2006.[187] Because many UAV components are produced in foreign countries, some experts fear that "back doors" could be surreptitiously built into American UAVs during the manufacturing process. Security experts indicate that China has already demonstrated the capability to engage in this type

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[186] Shachtman, 2011
[187] Singer, *op. cit.*, pg. 249.

of industrial espionage.[188] Such "back doors" could exist undetected for long periods of time, during which the U.S. would become increasingly reliant on UAV usage in warfare. The foreign country could then bypass security measures using the "back door" at a convenient opportunity, disrupting UAV computer control systems or even taking over control to direct UAV attacks on U.S. forces. Additionally, such countries could simply stop manufacturing critical UAV components for the U.S. if hostilities occurred between the two countries. Lastly, such outsourcing facilitates foreign efforts to clone sensitive military technology and develop their own UAVs to use against the U.S.[189]

Examples of militants hacking into UAV systems already exist. In December 2009, the Wall Street Journal reported that Iraqi Shiite militants hacked into Predator UAV communication systems using SkyGrabber, an off-the-shelf software produced by a Russian firm.[190] Specifically, these militants intercepted and downloaded surveillance videos captured by the UAV cameras as the videos were being broadcast back to ground stations. Captured videos were later discovered on other militant computers in both Iraq and Afghanistan, thus prompting officials to conclude that militants around the world had generally acquired the proficiency to hack into UAV feeds. No U.S. operations were reported to have been compromised by the breach, but officials generally feared that militants could use the stolen videos to determine which locations were under surveillance and subsequently avoid them. In 2010, an Israeli newspaper reported that Israeli officials believed that such UAV surveillance feeds had not only been compromised by Hezbollah militants in 1997, but that these militants had additionally used the videos to determine which routes Israeli troops would take during a subsequent military mission.[191] The militants

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[188] *Ibid.*, pg. 249.
[189] *Ibid.*, pg. 250
[190] Gorman, Dreazen, and Cole, 2009
[191] Ronen, 2010

used this information to set up an ambush, killing 11 Israeli commandos. Given that such a scenario is known to have backfired in the past and given the fact that the militants were able to hack into UAVs using extremely cheap software, it is quite conceivable that experts in well-funded foreign intelligence agencies could exploit additional vulnerabilities in UAV computer systems to great advantage.

Although military officials claimed that this video security vulnerability was being fixed by encrypting UAV feeds, the fact that these feeds can be easily intercepted raises serious questions regarding the advisability of using remotely piloted UAVs for ISR operations.[192,193] Indeed, retired Navy officer Thomas Rath recently observed that it “takes only a couple of relatively simple portable receivers to alert the enemy that [a UAV] is searching for them and to reveal both the aircraft’s position and the nature of its scanning system.”[194] Thus, enemy forces need not understand the information contained within the encrypted feeds to take useful action; they can simply disperse and lay low until the drone has left the area. Additionally, enemy forces could potentially destroy the drone by firing a heat-seeking surface-to-air missile and hope for a lucky strike after detecting a nearby drone’s transmissions. Theoretically, such a tactic could even be employed against stealthy drones, such as the RQ-170, that are difficult to detect with radar.

In addition to attacks from enemy forces, self-inflicted electronic interference represents a serious threat to UAVs. Some experts are advocating that UAVs should be capable of engaging in electronic warfare, including jamming of enemy communications. If these electronic warfare systems are not carefully designed, American UAVs may accidentally be a threat to

[192] Gorman, Dreazen, and Cole, 2009, *op. cit.*
[193] Rath, *op. cit.*
[194] *Ibid.*

themselves.[195] Such missions would provide unique challenges for a vehicle that is remotely piloted from another location. The fear is that if UAVs jam communication signals, then UAVs could jam their own remote piloting signals.[196] Without proper safeguards, such an interruption would cause the UAV to continue jamming, uncontrolled, threatening to isolate the UAV in a manner that would be difficult to recover from. Such a rogue UAV could also potentially wander into the airspace of neighboring countries and interrupt their communications, causing unnecessary political backlash.

Unfortunately, the fear of rogue, uncontrollable UAVs is not unfounded. Given the transcontinental nature of the communication networks required to remotely pilot UAVs, operators frequently lose control of their vehicles.[197] Two high profile cases already exist of UAVs causing serious concerns by going "rogue" and unintentionally wandering into restricted airspace. In 2010, a Fire Scout UAV wandered into restricted Washington D.C. airspace after operators lost control, nearly causing fighter jets to be scrambled.[198] In 2011, a much more serious incident occurred when a technologically advanced RQ-170 drone stopped responding to operator commands and veered into Iranian airspace before crashing.[199] In addition to eliciting an angry response from Iranian officials who claimed that the U.S. had aggressively violated their airspace, the crash likely provided Iranian scientists with access to advanced U.S. stealth and imaging technologies. To prevent UAVs capable of performing electronic attacks from frying their own communication uplinks and causing similar incidents, such UAVs should have

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[195] Shaw III, *op. cit.*
[196] *Ibid.*
[197] Mulrine, 2011
[198] Bumiller and Shanker, *op. cit.*
[199] Starr, 2011

jamming equipment on their underside, and their communication equipment should be located safely on top of the UAV.[200]

The Stock-and-Flow diagram depicted in Figure 5 summarizes the dynamics highlighted so far:

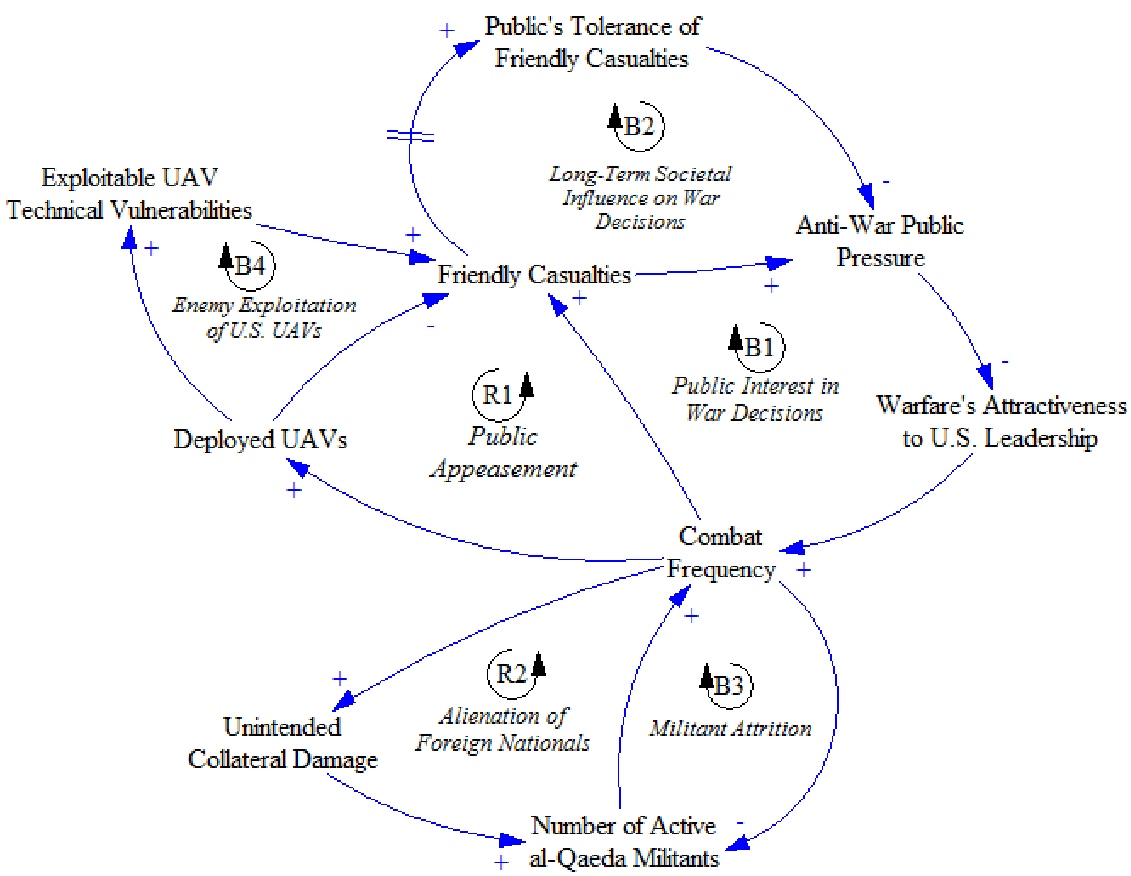

Figure 5: Dynamics of Exploitable UAV Technical Vulnerabilities: *This Causal Loop Diagram represents Figure 4 with the addition of the B4 loop, which indicates that the number of opportunities to exploit UAV technical vulnerabilities will increase as UAVs are increasingly deployed, which will ultimately lead to an increase in friendly casualties once the U.S. unexpectedly finds itself embroiled in conflicts in which UAVs cannot be used.*

[200] Shaw III, *op. cit.*

1.4.5 **Legal Ambiguity**

The use of UAVs in warfare could actually lead to more deaths because the state of legal accountability with regards to their actions is currently unclear under international law. The use of robotic weaponry in warfare is developing so quickly that international monitoring agencies, such as the International Committee of the Red Cross (ICRC), cannot keep up with the technology's impact on war. Typically, the ICRC has taken on the responsibility of ensuring that the most ghastly weapons are never used on tomorrow's battlefields. When deciding which weapons should be banned, the ICRC has four prescribed guidelines: (1) Nations can only engage in types of warfare that do not violate international law; (2) weapons that equally target both the military and civilians are banned; (3) weapons that cause unnecessary suffering are banned; (4) weapons that the international community finds to be terrible are banned.[201]

The Geneva Conventions mandate that a review be conducted on all new weapons prior to their use to ensure that they do not violate any of these guidelines.[202] While these guidelines have been enforced on many types of weapons, they have not yet been applied to the development and deployment of robots.[203] Notwithstanding the steady increase in robots' role in warfare after 2001, designers of robotic technology for military applications have not typically been instructed to consider these human rights issues during the initial design phase that international bodies use to judge other weapons of war. Thus, the technology driving robots' military uses seems to have bypassed the standard review process that ensures that weapons minimize civilian casualties and do not violate human rights.

[201] Singer, *op. cit.*, pg. 384.
[202] *Ibid.*
[203] *Ibid.*, pg. 385.

Perhaps more surprisingly, the ICRC has no official position whatsoever on how robots will affect human rights because despite their frequent recent use, the organization still views the technology as too futuristic to warrant serious consideration.[204] This sentiment was echoed by a U.S. official who stated that his lawyers indicated that there were no legal prohibitions on allowing robots to autonomously choose whether or not to kill a human.[205] Given these circumstances, no official positions on robotic warfare will likely be adopted until a tragedy occurs involving their use.

In addition to the uncertainty surrounding their development, serious legal gaps exist regarding robots' actual use in a war zone. For example, the accountability of robotic controllers' actions is entirely unclear. If a robot is used to commit a war crime or cause an otherwise unintended loss of life, it is currently unknown if the chain of command present at the battlefield is responsible for the actions or if the chain of command at the robot controller's location is responsible. It is also unclear if robotic controllers are legitimate targets of war. If they are, then their presence among civilian communities and the very families they live with may needlessly endanger civilians. This mixing of military and civilian targets risks increased collateral deaths if attacks on robotic controllers occur.

Legal questions are complicated by the numerous factors that support, even guarantee, the rapid increase in UAV autonomy. As UAV autonomy increases, human controllers will be too slow to react to the fast processing power governing enemy robotic actions, and thus, in order to survive, all combatants will be compelled to fully automate their robots to enable rapid electronically

[204] *Ibid.*, pg. 385.
[205] Weiner, 2005.

controlled counteractions without the human in the loop. Such reality already exists with Patriot Missile Batteries and the earlier-explained automated C-RAM systems that protect the Iraqi Green Zone from mortar and rocket fire. The use of fully autonomous robots in battle raises many unanswered questions regarding accountability in war. For example, as robots become more autonomous, the definition of war crime itself may have to be reexamined, as war crimes require both a violation and intent.[206] Because robots have no intentions, they technically can never commit a war crime. Indeed, autonomous robots likely could never fully replicate the complexities of human morality, which would make them capable of carrying out actions that humans would find too ghastly to commit.

Unfortunately, examples of semi-automated robots mistakenly killing humans already exist. In 1988, the computer-controlled Aegis air defense system of the U.S.S. *Vincennes* mistakenly identified an Iranian passenger plane as being an Iranian F-14 fighter, which led to the plane's destruction when the captain authorized the automated air defenses to engage.[207] A similar mistake occurred again in 2003 when U.S. Patriot Missile batteries accidentally shot down two U.S. Warplanes.[208] If a fully autonomous robot were to commit these types of tragedies, there is no policy in place to determine accountability, as it is unclear if the blame rests with the robot's manufacturer, artificial intelligence designer, or its user. The next generation of UAVs currently under development feature weapons that will be capable of combat with almost no human intervention, and because of the lack of oversight surrounding their development combined with the vast uncertainties surrounding their use, UAVs will be poised to administer unchecked death and destruction with no legal implications.[209]

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[206] Singer, *op. cit.*, pg. 389.
[207] Gray, 1997.
[208] Defense Science Board, 2005.
[209] Singer, *op. cit.*, pg. 117.

Figure 6 depicts a Causal Loop Diagram summarizes the dynamics outlined so far in the report:

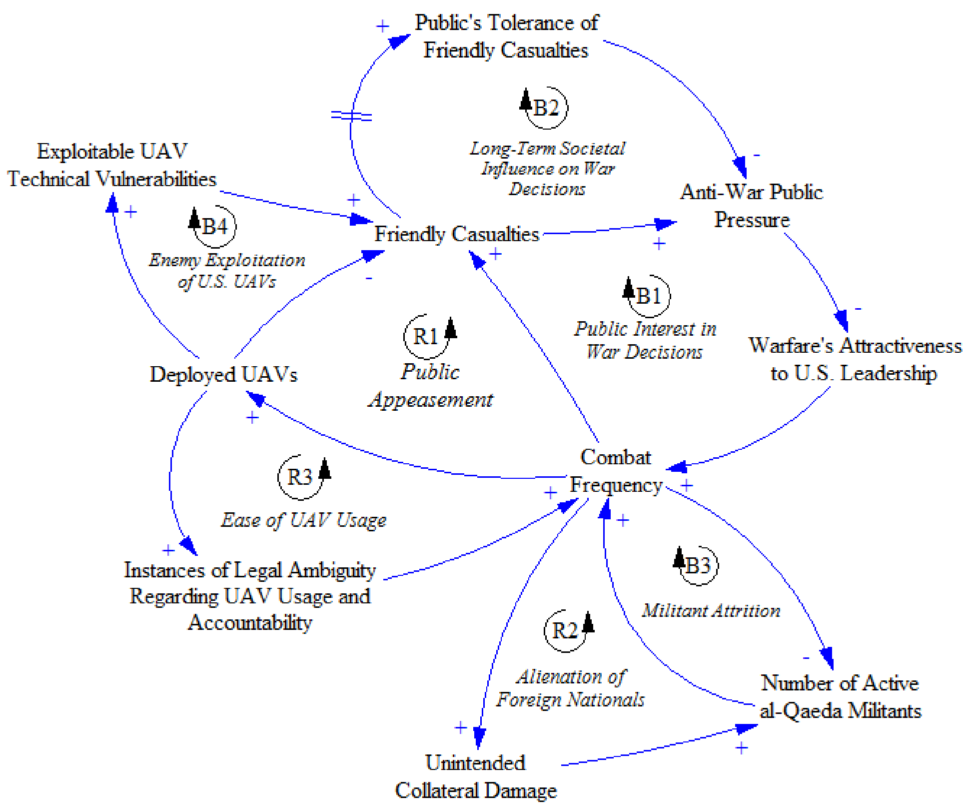

Figure 6*:*Dynamics of Legal Ambiguity of UAV Usage: *This Causal Loop Diagram represents Figure 5 with the addition of the R3 loop, which indicates that hostilities will be more easily initiated if no legal accountability governs UAV usage.*

1.4.6 **Increasing Range of Lethal Effectiveness**

In addition to the risk of facilitating more wars which will cause more overall deaths, UAV employment in warfare may ironically increase the loss of life in actual conflicts. Humans typically have a natural aversion to killing other humans that must be overcome with proper military training.[210] To counter this aversion, two common practices have been frequently used throughout history: (1) dehumanize the enemy, and (2) increase the distance at which killing takes place. The first practice is often accomplished through propaganda tools that paint an enemy force as being some kind of savage beast. For example, one United States World War I poster titled "DESTROY THIS MAD BRUTE" portrays a large, dark-skinned ogre-like creature wearing a standard-issue German Pickelhaube (spiked-helmet) while holding a distressed, half-naked, white-skinned woman in one arm.[211] Presumably, portrayal of the average German soldier as a monster and not an ordinary human would make civilians more willing to enlist and engage in lethal combat. Interestingly, as lethal UAVs increasingly populate battlefields, the enemy forces will not be entirely comprised of human soldiers, and thus the average human will have fewer reservations about engaging an enemy in combat. The resulting reduction of the violence threshold could ultimately lead to more death and destruction.

Historically, armies have relied on the practice of distancing soldiers from the enemy to remove the instinctive aversion to killing. This practice has been well-perfected over the past several thousand years, from the use of the bow and arrow to bomber aircraft. UAVs now place human controllers thousands of miles away from the combatants that they are killing. Similar to anonymous gamers or bloggers, the distancing of one's environs from one's actions could lower

[210] *Ibid.*, pg. 395.
[211] Hopps, c.1917.

the threshold at which lethal behaviors are acceptable.[212] The greater the extent that combat becomes simple abstractions on video consoles, the greater the impact that this distancing effect can have on human controllers to become completely unaffected by their own acts of killing. Indeed, a well-known phenomenon called "doubling" occurs when the separation distance changes how a user interacting with a virtual world views himself/herself and becomes capable of engaging in very uncharacteristic behaviors.[213] In conjunction with the emotional distancing, this change in behavioral patterns could increase the numbers of soldiers who engage in atrocities that they would otherwise not have been involved in had they been on the battleground. Taken together, dramatic behavioral changes caused by psychological distancing combined with the removal of risk and visceral battlefield horror threatens to create an atmosphere where war merely feels like a video game and killing is both enjoyable and glorified.[214, 215]

The Stock-and-Flow diagram in Figure 7 summarizes the dynamics outlined throughout the report:

[212] Shurtleff, 2002.
[213] Singer, *op. cit.*, pg. 396.
[214] Fumento, 2005.
[215] Shurtleff, *op. cit.*

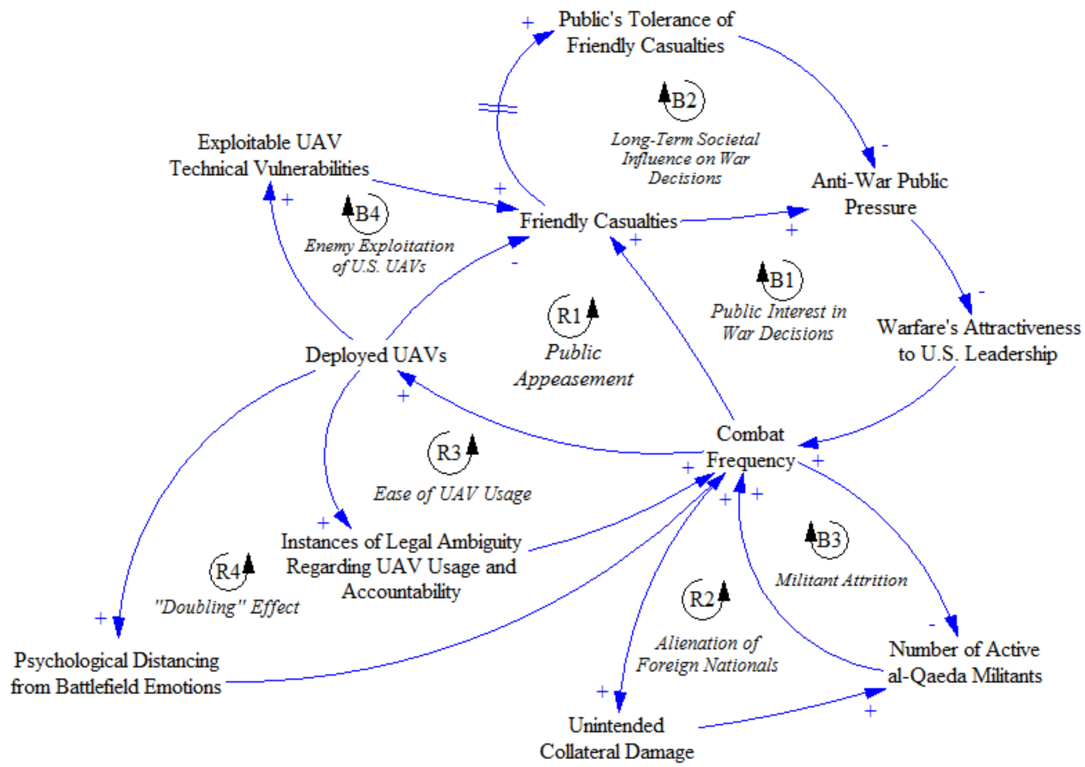

Figure 7: Dynamics of Psychological Doubling: *This Causal Loop Diagram represents Figure 6 with the addition of the R4 loop, which indicates that the psychological "doubling" associated with combat engagement through a virtual medium will increase the ease with which remote UAV pilots will be willing to perform lethal strikes through the removal of social and psychological inhibitions.*

1.4.7 UAV Technological Proliferation Places U.S. Critical Infrastructures at Risk

Although current small UAVs can provide the U.S. with low-cost, tactical strike capabilities, they can also be easily acquired and employed by U.S. adversaries. Such proliferation is already quite evident: as explained earlier, at least 40 countries are developing their own UAVs, with 10 additional countries maintaining a fleet of purchased UAVs. Unlike manned aircraft, widespread UAV acquisition is facilitated by the fact that UAV production does not require sophisticated engineering skills or production facilities.[216] Small UAVs can be carried and hand-launched by a single individual from any location, thus precluding the need for special supporting infrastructure.[217] They can deliver sufficiently destructive ordinance to attack lightly defended targets, and they are cheap and easy to assemble with exclusively off-the-shelf components.[218] For example, the UAV could be a remote-controlled model airplane wired with explosives and flown using video streamed to a laptop.

Examples already exist of groups and individuals creating or obtaining UAVs for a variety of purposes:

- In 2009, Sparkfun Electronics hosted an amateur autonomous vehicle race in which participants submitted homemade UAVs that were required to autonomously circumnavigate the Sparkfun building.[219] One UAV successfully completed the course in

[216] Riley and Means, 2006
[217] *Ibid.*
[218] *Ibid.*
[219] Grady, 2009

only 32 seconds.[220] Sparkfun held a similar race in 2011, with the stipulation that entrants could not spend more than $300 on their vehicles.[221]

- In 2005 a recent college graduate contacted several private defense contractors to explore the possibility of renting a UAV to help peace-keeping forces monitor genocide in Darfur.[222] Although he was interested only in ISR capabilities, this example may represent the first instance in which a private individual attempted to interfere in a foreign conflict using a UAV.
- In 2011, a U.S. citizen was arrested for planning to use a $6,500 radio-controlled model airplane to strike the Pentagon with 25lbs of C-4 explosives.[223]
- In 2006, the terrorist group Hezbollah penetrated Israel's sophisticated air defenses with potentially Iranian-made UAVs.[224] Israeli radar could not detect these UAVs because the UAVs were small and low-flying.[225] Two years earlier, a Hezbollah leader noted that these UAVs could be used to deliver 40-to-50 kilos of explosives to infrastructure targets, specifically citing power plants, water plants, and military bases.[226]

These examples illustrate that UAVs are easy to obtain from a variety of sources and can be loaded with explosives to strike targets. Most problematic is the fact that both lone-wolf terrorists and terrorist groups have obtained and planned to use UAVs against infrastructure targets. Additionally, such attacks would be very difficult to detect and thwart. If a terrorist launched such a UAV traveling 30 mph from 3 miles away, the target's defenders would only have 6 minutes to respond. In this scenario, the terrorist would both have a high chance of successfully executing the attack and subsequently escaping, thus increasing the appeal of such a tactic.

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[220] *Ibid.*
[221] "Remote Control War", *op. cit.*
[222] Zengerle, 2006
[223] "Man, 26, charged in plot to bomb Pentagon using model airplane", 2011 (see: http://www.cnn.com/2011/09/28/us/massachusetts-pentagon-plot-arrest/index.html)
[224] Riley and Means, *op. cit.*
[225] *Ibid.*
[226] Myers, 2005

UAVs could be employed against population centers and some critical infrastructures to great effect. Open-air events with large crowds, such as football games, could easily be targeted with a terrorist UAV strike. Although the primary attack would only produce a small number of casualties, the secondary panic and stampede could produce many more.[227] More frightening would be UAVs that are capable of dispersing chemical, biological, or radiological agents at such events. Aerial dispersion of easily-obtained pesticides in a crowded area would likely cause great panic. Alternatively, a UAV could contain sticks of dynamite wrapped with nails and cesium-137 powder, thus creating a flying "dirty bomb" that could be detonated virtually anywhere. UAVs could also be used to strike national monuments or passenger airliners as they are taking off or landing. Critical electrical and communication hubs could be struck, causing cascading downstream effects that would impede the proper functioning of other critical infrastructures, such as chemical processing, banking, water treatment, transportation, and emergency services, among others. An attack at a critical infrastructure or major public event would have long-term effects on public psychology and the national economy.

Despite the fact that all of these potential scenarios have already been discussed using other delivery mechanisms, the novel advantage of UAV delivery systems is cheap, rapid, easy penetration of sophisticated site defenses that were not designed to counter UAVs without exposing the attacker to capture. Given these advantages and given the mounting terrorist interest in UAVs for terrorist attacks, future vulnerability assessments and planning need to anticipate this tactic.

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[227] Weinberger, 2011

2.0 **Don't Blink: The Exponential Growth of Science and Technology**

"The Difference between science fiction and science is timing."

- Colonel Christopher Carlile, the former director of the U.S. Army's Unmanned Aircraft Systems Center of Excellence[228]

When looking throughout the course of history, timing has frequently been the critical element that distinguished a useful innovative idea from a laughable one. Virtually every technological advance would likely have been perceived as being unfeasible sometime prior to its eventual adoption for many reasons. For example, some advances simply do not seem possible against the backdrop of the current technological progress. The failure of the medieval age's greatest minds to conceptualize the modern laptop computer is but one of countless examples. Alternatively, technological advances may fail to develop because the advance fails to address a society's pressing need. In the first century A.D., Hero of Alexandria is believed to have invented the world's first steam turbine, known as the aeolipile.[229] However, the aeolipile was never adapted for practical use, in part because the widespread use of slavery throughout ancient Rome precluded any societal desire to find technological solutions for accomplishing work. Thus, an invention will be successfully adopted when it is technologically feasible and satisfies a societal need, both of which influence a technology's proper "timing."

Famous inventor Ray Kurzweil has made a science out of projecting technological trends after he noticed about thirty years ago that most technological advances and predictions usually fail because the proper timing is incorrectly perceived.[230] Kurzweil founded a business that centers on predicting future successful technological advances by properly accounting for the broader

[228] Austen, *op. cit.*
[229] "aeolipile", 2011
[230] Singer, *op. cit.*, pg. 95

contextual timing that would best-support the new technology. Instead of focusing on forecasting an array of very specific, minute advances, Kurzweil recognizes that the holistic parameters governing general technological change (i.e. "timing") are very predictable. Such a distinction is illustrated by the thermodynamics of making popcorn. While it is virtually impossible to predict when individual kernels will pop, one can easily predict when almost all of the kernels will have popped. Notable examples of successful forecasts include his early 1980s prediction that an obscure project called the ARPANET would blossom into the modern Internet. In 2002, Kurzweil's research group used technological data trends to predict that a pocket-sized reading device would be technologically feasible, even though the technology did not currently exist. The group ensured that its project would be ready by 2006 when the requisite technology had sufficiently matured to support their idea. Perhaps most relevant to this study, Kurzweil has described the use of military UAVs in Iraq and Afghanistan as "only an early harbinger" of a larger trend, noting that an upcoming age of robotics and artificial intelligence will "create qualitative change and social, political, and technological change, changing what human life is like and how we value it."[231] In 2002, Kurzweil shared with the U.S. Army his belief that robotics and artificial intelligence would become increasingly prevalent in war, but his vision "was seen as amusing, even entertaining."[232]

Such a dismissive response is puzzling at face value, as these army officers were plausibly aware of the potential for UAVs in combat. As was outlined above, drones had already been used effectively in the Kosovo war and were vital in the U.S.'s defeat of the Taliban government only a few months earlier. Additionally, the use of UAVs continued to increase rapidly post-9/11 and have been instrumental in weakening al Qaeda's ability to wage terror globally. Thus the

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[231] 2006, cited in Singer, *op cit.*, pg. 96
[232] 2006, cited in Singer, *op cit.*, pg. 96

situation begs the question – how could knowledgeable military officials so greatly underestimate the imminent rise of UAVs' importance in armed conflicts? The answer may potentially lie in psychological research demonstrating that humans are generally bad at forecasting trends that are changing at an exponential rate, which involves quantities that are changing at increasing rates over time. In two such studies, Wagenaar and Sagaria (1975) and Wagenaar (1978) discovered that people tend to significantly underestimate the growth rate of exponentially growing processes, causing them to project a linear growth rate throughout the future.[233,234] Such a finding means that people generally perceive growth rates as being fixed and unchanging, even if the rates are actually doubling after every time period. This phenomenon is well-encapsulated in a puzzle about a genie and the magically doubling penny. In this (sadly) hypothetical scenario, a genie appears before you offering a choice: you can take $1 million upfront, or you can take a magic penny that doubles in value every day for the next 30 days. Wagenaar and Sagaria (1975) and Wagenaar (1978)'s findings would suggest that respondents would likely take the $1 million, incorrectly predicting that the magic penny would not be as valuable after 30 days. However, performing the necessary calculations reveals that the magic penny would actually be worth over $10 million after 30 days. Examine the chart below diagramming the magic penny's value throughout the 30 days.

[233] Wagenaar and Sagaria, 1975
[234] Wagenaar, 1978

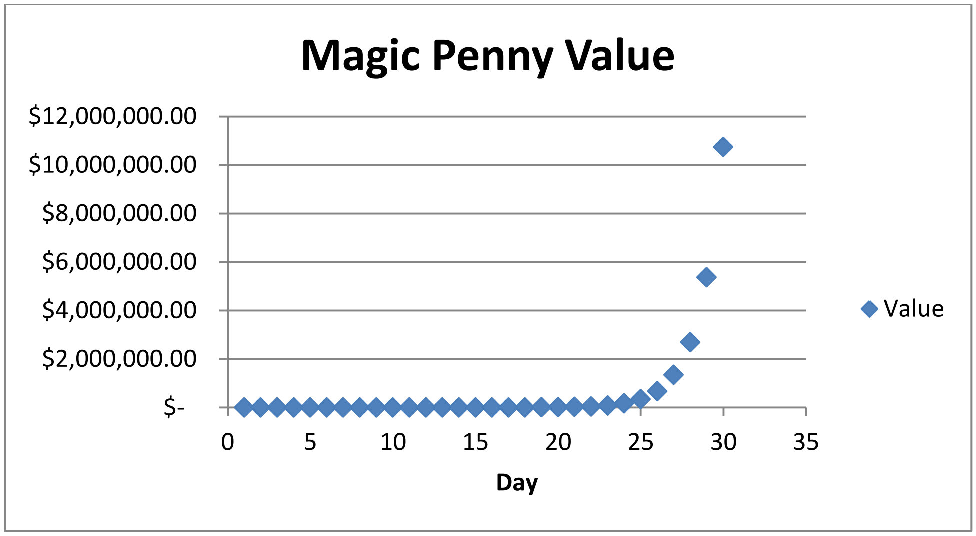

Figure 8: Magic Penny's Value throughout the Month: *This chart represents the exponential growth of the magic penny over a one month period. Note that the penny's value increases by large amounts at the very end of the month. Ultimately, the magic penny will be worth much more than $1 million.*

A major difficulty underlying improper choice selection is that the magic penny's value does not remotely surpass the alternative $1 million until day 27. Indeed, after 15 days have passed, the magic penny is still worth only a paltry $327.68. The following chart illustrates a roughly linear approximation of value's growth rate throughout the first 15 days, which is the incorrect projection that humans are reported to make.

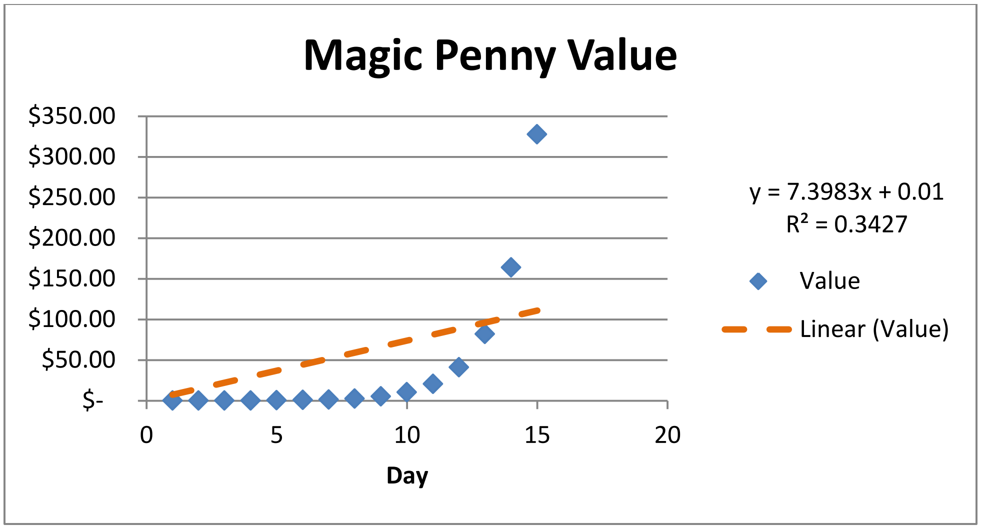

Figure 9: Psychological Misrepresentation of Exponential Growth: *People tend to approximate exponential growth linearly (brown dashed line). Quantities that grow exponentially exhibit initial linear growth before suddenly increasing by large amounts. Although people can roughly estimate initial exponential growth patterns during this pseudo-linear phase, they fail to anticipate the eventual departure from this pattern, on average.*

If a human approximates the growth rate utilizing the linear equation outlined above, then he/she would assume that the magic penny's value on day 30 would be $221.96, which is five orders of magnitude smaller than the correct answer. Because humans are so bad at correctly extrapolating exponentially, they generally fail to answer this puzzle correctly. Perhaps unexpectedly, follow-up research revealed that the underestimation worsened as more data was presented, and neither mathematical training nor familiarity with the exponentially growing process alleviated the underestimation.[235] Additionally, Lichtenstein and Fischoff (1977) demonstrated that people were 65% to 70% confident that they had correctly answered a number of questions correctly when they had actually done no better than the chance rate of 50%, thus scientifically demonstrating that humans can display overconfidence with their predictions.[236]

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[235] Wagenaar and Timmers, 1979
[236] Lichtenstein and Fischoff, 1977

Such studies may potentially lend valuable insights into why experienced and knowledgeable Army officials would scoff at the notion that UAVs were about to rapidly take center-stage in armed conflicts. Military experts may generally have underestimated the pace at which UAV technology would develop by failing to properly account for the fact that the technology is advancing at an exponentially growing rate. As Wagenaar and Timmers (1979) have shown, military officers' familiarity with a plethora of information relevant to growing UAV usage may have actually caused them to underestimate the growth trend of UAV usage to an even greater extent than the average person. To refer back to the magic penny metaphor, such experts may have assumed that UAV technology usage was roughly as advanced as day one, when the technology is actually closer to day 25 where it is poised for an explosive increase in real growth. Simple overconfidence obscures underestimation errors.

Compounding the difficulty of understanding the UAV technological growth was the fact that the military is highly conservative and arguably displays an obsession with doing things the way they have always been done. For example, the 1925 court-martial of Army Air Service Colonel Billy Mitchell for publicly denouncing the Navy and War Departments for negligence in the deaths of U.S. airmen in two separate disasters featuring the loss of U.S. aircraft demonstrated the military's discomfort with internal questioning of military policy.[237] Instead of engaging in a painful process of self-examination, the War Department tried and convicted Colonel Mitchell for violating the Ninety-Sixth Article of War, which prohibits conduct that discredits the military service.[238, 239] In a 1949 incident dubbed the "Revolt of the Admirals," three U.S. Navy admirals were fired for their desire to appropriate resources to build a new class of supercarriers (i.e.

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[237] Maksel, 2009
[238] *Ibid.*
[239] Ehrhard, 2010

business as usual) instead of long-range nuclear bombers needed for the upcoming Cold War.[240] A similar dispute occurred in 2008 when a high ranking U.S. Air Force official was reprimanded for "borderline insubordination" after he stated that he would purchase twice as many technologically advanced F-22 aircraft as had been authorized, despite their debatable utility in the War on Terror.[241] Thus, the UAV's increasing involvement in warfare may have simply been resisted by the military leadership because the technology was relatively new and threatened deeply entrenched operational modes of the establishment.

The belief that an imminent technological revolution will shape the next generation of military robots is certainly justified. Technological change was recognized to be growing at an exponential rate as early as 1965 when Gordon Moore, a cofounder of Intel, recognized that the number of transistors on a microchip was roughly doubling every two years.[242] This phenomenon was significant because, not only did the increasing number of transistors increase computer processing power, but their growing density reduced the distance that electrical currents traveled between any two given transistors, also increasing processing speed. Exponentially-growing processing power means that a standard computer today has more processing power than all of the mid-1960s Pentagon computers combined.[243] Indeed, one present-day supercomputer named "Purple" can do a number of calculations in six weeks that would take a supercomputer ten years ago nearly five thousand years to complete. The Department of Energy has already contracted IBM to construct a new supercomputer that can perform calculations ten times faster than Purple.

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[240] Jogerst, 2009
[241] Schachtman, 2008
[242] Singer, *op. cit.*, pg. 97
[243] Singer, *op. cit.*, pg. 98

With exponentially growing processing power comes exponentially decreasing costs. The cost of computer storage is decreasing by roughly 50 percent every fifteen months.[244] It took Intel thirty-five years to produce one billion microchips and only four more years to produce the next one billion. A cell phone's computational power is currently "a thousand times greater and a million times less expensive than all of the computing power housed at MIT in 1965."[245] In twenty years, computers will likely have a million times more computational power than computers today. Similar to how transistors and integrated circuits revolutionized electromechanical computational methods, current research in carbon nanotechnology, optical computing, and quantum computing promises to drive the exponential growth of future digital hardware for the foreseeable future.

Technology's exponential growth has not been restricted to computer applications. The United States Patent Office estimates that the annual number of important discoveries has doubled roughly every twenty years.[246] Additionally, wireless capacity is doubling every nine months, internet bandwidth is doubling every twelve months, the number of human genes mapped doubled roughly every eighteen months during the human genome project, and the resolution of brain scans is doubling every twelve months. This latter point is particularly relevant, as advances in neuroscience relate to the advance of artificial intelligence. Indeed, assuming that technological advances continue to grow at an exponential trend, computer capabilities will likely overtake the human brain's computational power sometime between 2025 and 2030.[247]

[244] Singer, *op. cit.*, pg. 99
[245] Kurzweil, 2008
[246] Singer, *op. cit.*, pg. 99
[247] Kurzweil, *op. cit.*

Some exponential advances are unequivocally military-driven. For example, modern-day bomber planes have roughly half a million times the killing capacity of a classical Roman soldier.[248] During World War II, about 108 planes were required to strike a single target, but by the beginning of the 2001 Afghanistan War, a single plane was destroying 4.07 targets on an average flight. These exponential growth rates indicate that rapid changes will not only continue to occur over the next few years, but the resulting discoveries may be more advanced than we might otherwise expect if we falsely assume the growth rates to be linear. For example, when scientists planned to sequence most of the human genome in a fifteen year span, many mocked the project when only 1% of the human genome had been sequenced by the halfway point.[249] However, because critics did not account for the fact that the project's pace was doubling every year, they were quite surprised when the entire genome was sequenced on schedule after fifteen years.

High-profile science-fiction movies such as Terminator, The Matrix, and iRobot have undoubtedly served as inspiration for the fields of robotics and artificial intelligence. It is unlikely that UAVs will resemble these fictional stories any time in the near future. However, the point is that technological fields – specifically robotics and artificial intelligence – will exhibit increasingly larger numbers of advances over the next few years. The overall evolution of technological capabilities throughout the next two decades will likely be far greater and more impressive than anyone imagined. Thus, what is currently science fiction today may become reality sooner than anyone thought possible. Such technological advances will directly impact the burgeoning use of UAVs in combat settings by expanding their military effectiveness and autonomous capabilities.

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[248] Singer, *op. cit.*, pg. 100
[249] Singer, *op. cit.*, pg. 97

2.1 The Rise of Artificial Intelligence

"I'm sorry, Frank, I think you missed it. Queen to Bishop three, Bishop takes Queen, Knight takes Bishop. Mate…Thank you for a very enjoyable game."

-HAL (*2001: A Space Odyssey*)

In addition to rapid technological advances that enable increasingly powerful computer hardware, artificial intelligence (AI) software must also be developed to power future UAV autonomy. Although the notion that artificial intelligence rivaling the human capacity for intelligent thought has been exclusively the realm of science fiction, the exponentially growing number of technological advances may plausibly create the proper conditions for realizing this possibility. A historic analog is the progression of human flight from a centuries-old fantasy to actuality due to technological progress in multiple supporting areas.

For UAVs to successfully interpret complex, confusing environments and make appropriate decisions, future AI must be able to dynamically acquire multi-faceted sensory information from the environment and analyze the integrated information to interpret the surroundings and select behaviors appropriately. Because real world environments and situations are only partially predictable, future AI must be able to categorize the constituent features of its detected sensory inputs and make generalizations based on past experiences and mental models, which is functionally equivalent to higher-level human cognitive functioning.

While creating AI that can successfully analyze and operate within real environments is very challenging, some high-profile advances have occurred in the past 15 years. In 1997 – and some

29 years after HAL beat Frank at chess in the *2001: A Space Odyssey* film – IBM supercomputer Deep Blue defeated the reigning world chess champion Garry Kasparov after six matches.[250] Although technologically complex, the machine's ability to interpret the environment was conceptually simple. Because chess is played using a precise set of rules and because there is very little dynamically changing information from the actual environment (i.e. the chess board), the AI can be programmed to always recognize and interpret all relevant information when selecting each move, thus greatly simplifying the design requirements. Armed with perfect knowledge about the environment, Deep Blue relied on "brute force" to analyze 200 million positions per second when selecting the best move, a strategy that humans cannot employ due to biological constraints. Deep Blue may not have found the game "very enjoyable," but its victory nevertheless marked a significant milestone in the quest for AI that could surpass human abilities at a specific task.

In 2011, another IBM AI named Watson entered the history books when it defeated the top two all-time "Jeopardy!" champions in a televised game of "Jeopardy!"[251] Watson was designed to be a "question answering" machine capable of understanding and correctly answering questions posed in everyday human language.[252] Given the complicated nature of "Jeopardy's!" question phrasing, IBM researchers viewed the game show as an ideal tool for developing AI that can better-understand natural language. With its numerous nuances, ambiguities, and complexities, computer comprehension of natural language is a research area that has remained elusive to computer scientists over the decades.[253] Such a nebulous problem is significantly more difficult for a computer to handle than chess playing, as the rules and mathematics behind chess are well-

[250] For more information, visit IBM's website at http://www.research.ibm.com/deepblue/
[251] See http://www-03.ibm.com/innovation/us/watson/what-is-watson/index.html
[252] Thompson, 2010
[253] Jackson, 2011

defined.[254] Additionally, Watson had to understand and answer the questions in a few seconds to be competitive with the human contestants. With 2,800 processor cores and 16 terabytes of working memory, Watson can process 80 trillion operations per second.[255]

Watson had to successfully operate in an extremely complex "environment," as "Jeopardy's!" subject matter could include anything from human knowledge. Such a limitless array of potential questions prevented the preprogramming of questions and answers within Watson's knowledge database. To deal with this issue, the equivalent of 200 million pages of data was stored into Watson's "brain," and statistical algorithms were used to identify associations between relevant names, words, and phrases that frequently appeared together in the data in response to a particular question.[256] Such an ability to recognize meaningful associations allowed Watson to recognize inferences and relationships that are not explicitly stated in the question. For example, if a potential "Jeopardy!" clue was: "The name of this hat is elementary, my dear contestant," Watson could recognize that part of the clue resembles the famous phrase "elementary, my dear Watson," which is commonly associated with Sherlock Holmes.[257]

Such statistical strategies are not new, but Watson's tremendous speed allowed it to utilize roughly a hundred different algorithms simultaneously to search for the correct answer.[258] A second set of algorithms estimates the plausibility of each potential answer, and a particular answer is typically favored to the extent that the various search algorithms converge upon it.[259] If

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[254] *Ibid.*
[255] Thompson, *op. cit.*
[256] *Ibid.*
[257] *Ibid.*
[258] *Ibid.*
[259] *Ibid.*

Watson did not estimate that it was sufficiently confident in its answer, then it chose not to respond.

Although the questions that Watson can answer are strictly objective facts devoid of any judgments, Watson's ability to understand language, parse complex syntax, and correctly find the correct answer to a question in its immense memory storage in only a matter of seconds is a phenomenal breakthrough in artificial intelligence that seemed unlikely only a few years ago. When initially briefed about designs for creating Watson, IBM executives reportedly dismissed the idea outright as being too difficult.[260] Indeed, such an example demonstrates that even some of the best-informed experts in the world do not always recognize the rate at which artificial intelligence is being developed. After some convincing, a team of 15 IBM employees was assembled in 2007 to create Watson. It only took them four years to finish the project and achieve this ambitious goal.

In 2005, Sebastian Thrun and his Stanford research group won the Grand Challenge event hosted by the Defense Advanced Research Projects Agency (DARPA).[261] The event featured 195 teams from thirty-six states and four countries, each competing for the $2 million grand prize. The object of the challenge was to design an autonomous robotic vehicle that could successfully navigate a 132-mile off-road course through Nevada's Mojave Desert.[262] Among the challenge's main stipulations was that the robotic vehicles could not receive any human intervention during the race.[263] Consequently, for a vehicle to be competitive, it had to be capable of dynamically perceiving its immediate surroundings and use the information to map the safest, most expedient

[260] *Ibid.*
[261] Singer, *op. cit.*, pg. 136
[262] Russell, 2006
[263] Singer, *op. cit.*, pg. 136

routes to reach the finish line. Stanford's winning vehicle, named Stanley, was equipped with a suite of detectors and controls, including five Laser Detection and Ranging (LADAR) sensors, GPS, three gyroscopes, three accelerometers, a video camera, and onboard computers with roughly 100,000 lines of code.[264, 265] The onboard systems used the sensors to construct a 3D model of the surrounding landscape, with which the AI could analyze to make decisions about where to travel.

During the early testing phases, Stanley exhibited a 12 percent false positive error rate by frequently classifying shadows and other benign features as impassable obstacles.[266] To reduce this error rate, Dr. Thrun's team implemented a unique innovation not found in the other vehicles: a learning and memory algorithm that incorporated its prior driving experience into all decision-making processes.[267] During trial runs, Stanley learned how to distinguish good routes from bad routes by capturing the reactions and decisions of human drivers, and it incorporated the humans' judgments when making autonomous decisions.[268] The ability to learn from experience tremendously increased Stanley's flexibility when encountering novel situations by making generalizations based on previous experience. Indeed, programmers would face an impossible task if they tried to hard-code a decision-making process for every possible situation that Stanley might face. After extensive training, Stanley's false positive rate was reduced to 0.00002 percent, thus allowing Stanley to travel for hundreds of miles error free.[269]

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[264] *Ibid.*, pg. 137
[265] Russell, *op. cit.*
[266] *Ibid.*
[267] Singer, *op. cit.*, pg. 137
[268] Russell, *op. cit.*
[269] *Ibid.*

The previous examples demonstrate that current artificial intelligence already displays tremendous analytical, learning, and memory capacities that would be crucial for future autonomous UAVs. Autonomy is a daunting proposition, and the previous examples of blooming artificial intelligence are bellwethers that future research can extend autonomy to military and intelligence applications. To successfully navigate confusing battlefields and extreme environments while executing missions, UAVs must sense the environment, process and remember important stimuli, problem solve and respond to the perceptual environment accordingly, and adapt future behaviors to past experiences. Most crucially for full autonomy, UAVs will be required to make human-like judgments regarding ambiguous stimuli in a manner that minimizes mistakes and unnecessary harm to friendly forces and civilians. Indeed, recent examples from the CIA's drone program in Pakistan suggest that UAVs will be operating in environments where enemy militants are extremely difficult to distinguish from civilians for the foreseeable future.

Although much literature has been published regarding the rise of UAV autonomy in recent years, very little attention has been publicly paid regarding *how* autonomy can be successfully implemented in UAVs; viz. how do UAVs acquire such decision-making abilities? To develop sufficient artificial intelligence, one need only look to neuroscience for answers. The human brain is well-equipped to handle these same challenges, and thus serves as a useful model for developing necessary artificial intelligence. The problem is challenging because emulating biological neural systems represents a dramatic departure from how normal computer systems operate, as the two have several fundamental differences. For example, digital computers generally contain a central processing unit (CPU) and a memory store. The CPU fetches data from memory, performs simple operations, and stores the output back into memory.

Consequently, computers carry out complex operations by executing millions of operations per second *in series*.[270]

In the human brain, there are no clearly-defined memory and processing locations, as the two coexist within individual neurons. These cells receive electrochemical inputs from upstream neurons and send electrochemical signals to activate downstream neurons.[271] This process repeats cyclically, thus creating a chain of signaling that passes information through a coupled network of neurons. These cells are concatenated in large, densely interwoven networks throughout the central nervous system.

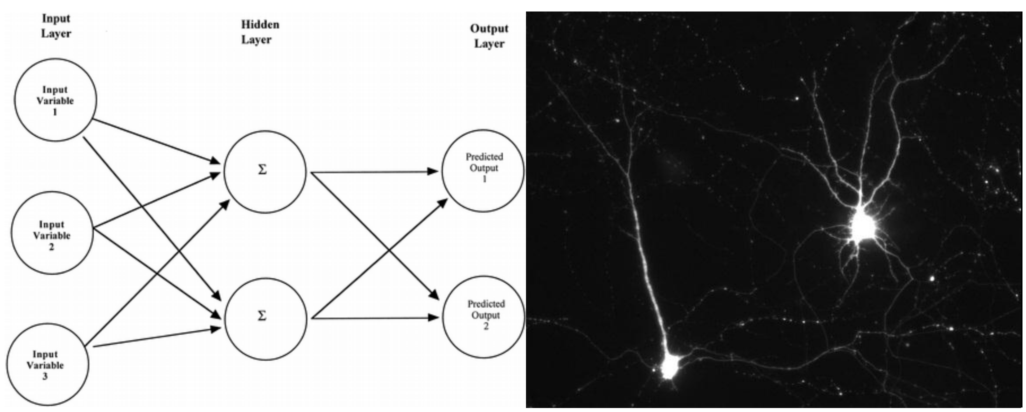

Figure 10: Simple Biological Neural Network Overview: (Left) *A conceptual schematic of a simple biological neural network is outlined above, with each circle representing a neuron and each arrow representing a neural connection. Input Layer neurons typically represent sensory neurons that receive specific inputs from the environment and pass the information to interneurons within the Hidden Layer. These interneurons combine and filter the information that they receive from multiple sensory inputs before ultimately selecting an appropriate action by passing the filtered information to a neuron that initiates a behavioral output (Output Layer). More complex neural networks feature multi-layered networks with many additional interneurons and connections. Consequently, information processing occurs at each neural connection as complex stimuli features are decomposed and simultaneously processed.*[272]

[270] Lieberman, 2004
[271] For a detailed review of neuronal signaling, see Squire et al., 2003
[272] Picture Source:
http://www.google.com/imgres?start=149&um=1&hl=en&sa=N&biw=1366&bih=644&tbm=isch&tbnid=zGEgkTkl2NIMBM:&imgrefurl=http://psycnet.apa.org/journals/apl/84/2/177.html&docid=xts6261wX3MPAM&imgurl=http://psycnet.apa.org/journals/apl/84/2/images/apl_84_2_177_fig1a.gif&w=462&h=350&ei=8hpPT4mCMoHq0gGFpOm9DQ&zoom=1&iact=hc&vpx=364&vpy=25&dur=2108&hovh=195&hovw=258&tx=110&ty=214&sig=111567982290281819681&page=7&tbnh=139&tbnw=183&ndsp=25&ved=1t:429,r:1,s:149

(Right) *A confocal microscopy image of two neurons extracted from a rat brain and transfected with Green Fluorescent Protein to make them visible. Notice the extensive branching patterns of each neuron which constitutes the inputs and outputs to other neurons within the network.*

The brain is estimated to contain 100 billion neurons, with each neuron receiving inputs from 1,000 to 10,000 other neurons.[273] Such figures suggest that the human brain could contain up to 1,000 trillion connections. Unlike computers, biological neural networks can solve complex problems by simultaneously performing millions or billions of operations *in parallel*.

Thus, differences in architecture between computers and biological neural networks force these systems to solve problems using very different strategies. Consequently, such differences allow biological neural networks to easily solve problems that are extremely difficult for computers. For example, humans can generally read each other's handwriting with ease, despite the various nuances and styles afforded to individual characters unique to each person. By contrast, most computers cannot perform this simple task.[274] However, evidence has surfaced in recent years indicating that specialized computer hardware is already being developed to mimic biological neural networks and capitalize on the advantages that such networks afford to problem solving. For example, although far inferior to the parallel processing found in the human brain, Watson's 2,800 processor cores allows it to perform many decision-making algorithms simultaneously, thus increasing both the machine's speed and accuracy.

In August 2011, IBM announced its newest creation: two prototype computer chips that are "designed to imitate the human brain's ability to understand its surroundings, act on things that

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[273] See http://faculty.washington.edu/chudler/facts.html#neuron, accessed 10/7/2011
[274] Lieberman, *op. cit.*

happen around it and make sense of complex data."[275] Such hardware will "let a new generation of computers, called 'cognitive computers,' learn through their experiences and form their own theories about what those experiences mean."[276] One of these cores contains 262,144 artificial programmable synapses, and the other contains 65,536 "learning synapses."[277] Ultimately, IBM researchers hope to develop a one-square-centimeter chip containing 1 million artificial neurons with 10 billion total connections, indicating that 10,000 connections would exist per artificial neuron, on average.

This technology emulates the neural connectivity found in human brains. Considering that in 2007, the combined processing power of all the world's computers was estimated to be equivalent to the processing power of one human brain, the creation of these advanced chips would be very impressive.[278] IBM researchers believe that such chips could serve as sensors that could monitor environments and report interesting activity that deviates from a desired state. For example, the chips could monitor the sights, smells, and temperature to ensure that grocery store produce is still fresh or send an alert to the appropriate authorities if it learns through observation that a given traffic intersection is dangerous.

Complementing such revolutionary hardware, the Intelligence Advanced Research Projects Agency is currently funding the development of project ICArUS, a computational model that represents how seven major brain systems interact to produce "the human ability to draw inferences from data that is sparse, noisy, and uncertain."[279] Such a model would ideally have the

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[275] Gross, 2011
[276] *Ibid.*
[277] *Ibid.*
[278] Hilbert and Lopez, 2011
[279] Jean, 2011

ability to predict the idiosyncrasies of neural processing involved in interpreting data, such as cognitive bias. Consequently, such a model could improve human decision-making by alerting humans when bias is likely to interfere with judgments, and it could even perform routine analysis, thus freeing human analysts to perform other tasks.

Although both IBM and the Intelligence Advanced Research Projects Agency's research is aimed at supporting human tasks, the handwriting is on the wall: in this new era of military robotics, such increasingly intelligent computer hardware and computational models will inevitably find useful homes in automated UAVs. The ability to learn from experience, perform analysis, form theories about the meaning of experiences, and execute actions based on complex analysis are all clearly important traits in truly autonomous systems. For example, a UAV could recognize behavior resembling the planting of an improvised explosive by accounting for the observed actions, the region's history regarding such attacks, and the frequency that similar observed behavior has led to the discovery of an improvised explosive device. If the UAV is sufficiently convinced with a great degree of confidence that such a hostile act is occurring, it could execute a lethal strike. For example, the UAV could run facial and voice analysis to determine if the suspect is a known militant. It could then calculate the blast radius that would result from deploying each weapon in the UAV's arsenal and select the weapon, time, and location for executing the lethal strike that minimizes collateral damage and civilian casualties. If the UAV needs more information, it could alert the appropriate authorities to the location of the suspected improvised explosive device, follow the suspect, and gather additional information about the suspect's "pattern of life", not so dissimilar from what human UAV operators do today.[280]

[280] Shane, *op. cit.*

The suspect's behaviors and tendencies could also be analyzed to locate additional suspicious behavior or useful intelligence. For example, does the suspect interact with other known militants? Does the suspect possess outlawed weapons? Does the suspect routinely plant strange objects near roads frequented by U.S. soldiers? Does the suspect place phone calls in which he/she admits to partaking in militant actions? Was an improvised explosive device ultimately found at the location the suspect was first spotted? Thus the UAV would analyze all relevant behaviors when deciding which actions to perform. If the drone ultimately concludes that the suspect is hostile, it could engage in a lethal strike at a time that would maximize the number of known hostiles killed while minimizing collateral damage, based on the "pattern of life" analysis. If the analysis is ultimately inconclusive, the drone could still file a report about its suspicions to the proper authorities.

The ability to emulate the biological brain and human cognition is clearly a fruitful objective, as is evident from the IBM and the Intelligence Advanced Research Projects Agency's latest research projects. Such a goal clearly has advantages for UAVs, as it allows UAVs to perform complex analysis and actions with decreasing human oversight. How exactly does artificial intelligence software support such human-like cognitive abilities? This question will be addressed in the next section

2.2 **Neural Networks – An Ideal Artificial Intelligence Architecture for Autonomous Systems**

To operate autonomously in complex, confusing environments, there are compelling reasons to design UAV artificial intelligence to emulate the operation of the human brain's neural network. Building on the previous section's explanation of the architectural differences between neural networks and standard computer functioning, the current section explores *how* neural networks function to produce human cognition and human-like cognitive abilities in artificial systems and why these abilities are important in achieving UAV autonomy.

According to Lieberman (2004), artificial neural networks are simple systems that have three basic features:

(1) The network is composed of interconnected neurons, with each neuron connecting to every other neuron in the simplest networks.

(2) When a neuron is activated, the activity is transferred to other neurons connected to it in a manner proportional to the strengths of each connection. (e.g. if neuron A is strongly connected to neuron B but weakly connected to neuron C, then activation of neuron A will transfer a large amount of activation to neuron B but a weak amount of activation to neuron C.)

(3) If two neurons are simultaneously active, their connection with each other strengthens, thus increasing the likelihood that future activation of one neuron will correspondingly activate the other.[281]

[281] Lieberman, *op. cit.*, pg. 479.

Not surprisingly, such features strongly resemble both research in biological neural networks and Pavlov's assumptions when he described an associative learning process – called classical conditioning – in biological organisms roughly 100 years ago. In a typical classical conditioning paradigm, an initial neutral stimulus called a conditioned stimulus (CS) is paired with a biologically important event called an unconditioned stimulus (US). In a hypothetical learning paradigm characterizing early psychological research, the test subjects might be rats, the CS might be presentation of an audible tone, and the US might be presentation of brief electric shock. After a number of CS→US pairings, the CS acquires the ability to elicit a new learned response called the conditioned response (CR). For example, freezing (cessation of body movement) is a prominent defensive fear reaction in rodents. Through classical conditioning in which a tone is repeatedly presented with shock (tone→shock) in rats, the tone can acquire the ability to elicit defensive freezing when presented alone. In the modern analysis of associative learning, classical conditioning results in the formation of associations between memory representations of the CS and US.[282, 283] In the present example, the rat freezes when the tone is presented because the tone activates a memory of the shock. Because the shock is stressful, the animal engages in defensive freezing.

To translate this scenario into biological terms, presentation of shock activates the "US" neuron, which is hard-wired from birth to activate the response or "R" neuron, thus eliciting the freezing behavior. The "CS" neuron is activated by the tone, and before learning has occurred, CS neuron's activation does not increase R neuron's activation. However, after CS neuron and US neuron are simultaneously activated by several tone→shock pairings, the connection between CS

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[282] Rescorla, 1974
[283] Mackintosh, 1983

neuron and US neuron becomes strengthened, thus allowing the CS neuron to reliably activate the US neuron, which in turn activates the R neuron (CS neuron→US neuron→R neuron). In other words, the tone acquires the ability to elicit the freezing response by acquiring the ability to activate the neural circuitry that produces a behavioral response to shock.

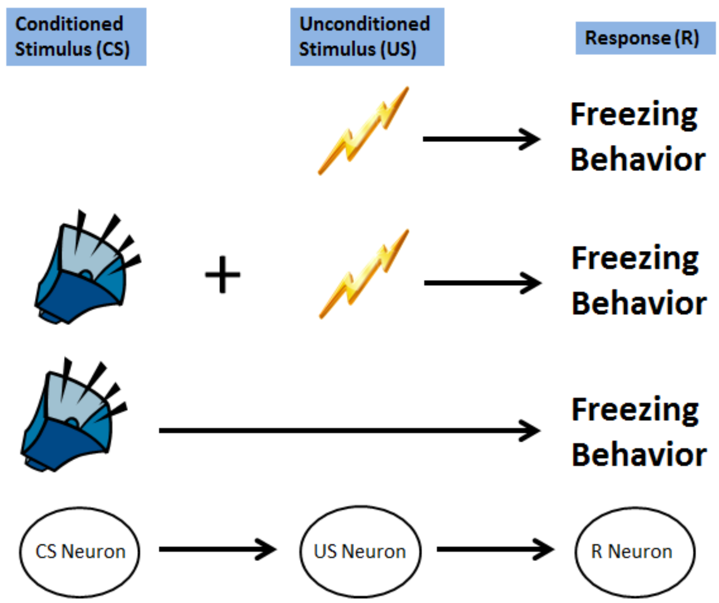

Figure 11: Classical Conditioning Overview: *Illustrated above is a standard classical conditioning paradigm. A previously neutral stimulus (Conditioned Stimulus) acquires the ability to elicit a response after it has been paired with the presentation of an Unconditioned Stimulus that naturally elicits a response. Conceptually, the Conditioned Stimulus, Unconditioned Stimulus, and the Response can all be mapped to individual neurons. After the co-presentation of the Conditioned and Unconditioned Stimuli, the CS and US Neurons become simultaneously activated, causing the connection strength between these two neurons to be increased. Consequently, the subsequent activation of CS Neuron alone will activate the US Neuron, which will activate the R Neuron, producing the behavioral response.*

Naturally, classical conditioning analysis is not restricted to rats. Because classical conditioning can involve the acquisition of new fear behavior in humans[284], considerable research has been directed to understanding the extent to which classical conditioning of fear might underlie human fear and phobias.[285, 286, 287, 288, 289, 290] Basically, classical conditioning is a kind of predictive

[284] Watson & Rayner, 1920
[285] *Ibid.*
[286] Bouton, 2002
[287] Bouton & King, 1983

learning in which organisms can learn to predict the future occurrence of biologically important events. In this context, some have suggested that classical conditioning represents a mechanism that enables organisms to learn the causal structure of their environments.[291]

Biological research into neuronal signaling supports the hypothesis that neural connectivity can dynamically change based on the simultaneous activation of two connected neurons. Specifically, Long Term Potentiation (LTP) is the molecular phenomenon that mediates these changes in connectivity at the synaptic junctures that serve as the functional interfaces between biological neurons. Synapses in the hippocampus contain N-Methyl d-aspartate (NMDA) receptors, and research has implicated these receptors as having a key role in LTP.[292] The NMDA receptors specifically bind to the neurotransmitter Glutamate, a signaling molecule in the nervous system that transfers information (i.e. activation) across the synaptic gap separating two neurons.

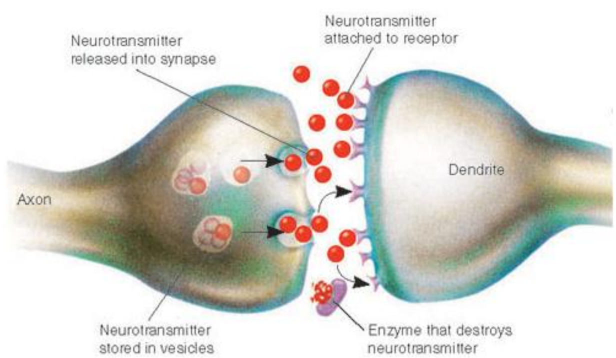

Figure 12: Synaptic Transmission Overview: *This diagram represents normal synaptic transmission (i.e. information passing) between two neurons. Notice that these neurons are not physically connected, and are thus divided by a gap (synapse). To get information across the gap, the neuron on the left (presynaptic neuron) releases neurotransmitters (red circles) that float across the gap via passive diffusion. Protein complexes (receptors) located on the surface of the right neuron (postsynaptic neuron) physically bind to the neurotransmitters if they happen to randomly come into*

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288 Bouton & Nelson, 1998
289 Seligman & Maier, 1967
290 Seligman, 1971
291 Mackintosh, *op. cit.*
292 Morris, Anderson, Lynch, & Baudry, 1986

contact. This binding changes the 3-dimensional structure of the receptor complex, thus forming a membrane pore that allows ions to enter the postsynaptic neuron. This ion influx initiates a chain-reaction of events that passes information through the postsynaptic neuron, which will then signal additional neurons in the network via this same mechanism.[293]

Initial binding of glutamate to NMDA receptors has a surprising result – no activation of the postsynaptic neuron occurs. However, earlier research of general LTP mechanisms in other areas of the central nervous system had revealed that the NMDA receptors were blocked by magnesium (Mg^{2+}) ions.[294] Thus, the glutamate molecules were successfully binding to the receptor and the receptor properly changed its conformation to reveal a pore through the cell membrane, but calcium (Ca^{2+}) ions were unable to pass through because Mg^{2+} blocked the pore.

However, this blockage could be eliminated through the activation of a second receptor, known as the alpha-amino-3-hydroxy-5-methyl-4-isoxazolepropionic acid (AMPA) receptor, which also forms a (unobstructed) pore through the cell membrane allowing sodium (Na^{+}) ions to pass into the postsynaptic neuron. If sufficient activation of AMPA and NMDA receptors occurs simultaneously, then the Mg^{2+} molecule will be expelled out of the NMDA receptor, thus removing the pore blockage. This expulsion allows Ca^{2+} to enter the postsynaptic cell via the NMDA receptor channels and triggers the insertion of even more AMPA receptors into the postsynaptic membrane and increases the excitability (i.e. propensity to produce activation) of previously existing AMPA receptors.[295] This increase in AMPA receptors makes the postsynaptic neuron more sensitive to future glutamate release, and thus, more easily activated. Highlighting their role in learning, research has shown that blocking NMDA receptors in rats blocks spatial learning.[296]

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[293] Picture Source: http://mindblog.dericbownds.net/2007/07/novel-environments-stimulate-memory.html
[294] Mayer, Westbrook, & Guthrie, 1984
[295] Esteban, 2003
[296] Davis, Butcher, and Morris, 1992

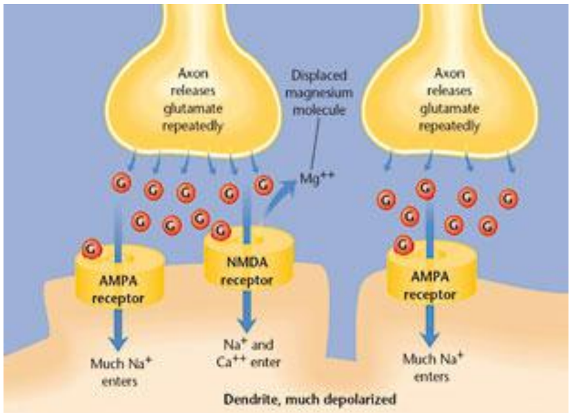

Figure 13: Long-Term Potentiation Overview: *This diagram illustrates the dynamics of NMDA and AMPA receptors. The glutamate neurotransmitter (red circles) are capable of binding to both of these receptors upon contact, creating a pore for ion travel through the postsynaptic neuron membrane. However, ions cannot initially pass through the pore complex formed when glutamate binds to the NMDA receptor because the pore is blocked by a magnesium (*Mg^{2+}*) ion. Once glutamate facilitates sodium (*Na^{+}*) passage through the postsynaptic membrane by binding to AMPA receptors, the* Mg^{2+} *ions will be expelled from the NMDA receptor pores as long as the NMDA receptors are bound to glutamate molecules. Once the NMDA pore has been cleared, calcium (*Ca^{2+}*) ions can enter the postsynaptic neuron through the NMDA receptor and induce both short-term and long-term changes that make the postsynaptic neuron more responsive to future activation from the presynaptic neuron.*[297]

LTP is a robust phenomenon that can last from hours to years. The increasing number of AMPA receptors in the postsynaptic neuron's membrane and modifications to their protein structures accounts for the initial increase of synaptic strengthening (i.e. strengthening of the connection between the two neurons)[298, 299], but other factors increase this effect over longer durations. The NMDA-mediated Ca^{2+} influx into the postsynaptic neuron activates cAMP response element binding protein-1 (CREB-1), a transcription factor that ultimately activates further DNA-mediated protein synthesis (i.e. gene expression).[300] This additional protein synthesis is a relatively slow process, but it leads to robust structural modifications to signaling elements along the synapse that maintain LTP for long durations. The delayed onset of protein synthesis and the initial insertion of more AMPA receptors in the membrane could potentially represent a difference in short-term memory and long-term memory mechanisms.

[297] Picture Source: http://www.vpt-physio.com/detailseite.cfm?MeldungsID=552
[298] Hayashi, 2000
[299] Lu et al., 2001
[300] Poser and Storm, 2001

In addition to identifying the molecular mechanisms that can account for the rapid induction and maintenance of LTP, research has also identified a mechanism that is responsible for the selective associative aspects of LTP. Scientists have found evidence that local protein synthesis in the postsynaptic terminal following the initial induction of LTP serve as a “synaptic tag” that is required for capturing the products of the CREB-1 induced protein synthesis (via gene transcription).[301] These synaptic tags last for only a few hours, and they serve as a mechanism for selectively enhancing only those synapses that were involved in inducing the initial LTP. Additionally, multiple synapses can acquire the necessary synaptic tag simultaneously if all of the synapses contributed to the depolarization of the postsynaptic neuron.

Synaptic tagging potentially allows multiple stimuli to be associated with each other in memory, thus allowing complex memories to be broken into functional units and distributed throughout the neural network. For example, a functional area of the human brain known as the hippocampus plays a key role in non-discreet contextual memory formation (e.g. subtle environmental features, such as lighting, smell, olfaction, and texture, among many other possibilities)[302], which could simply be represented as a collection of various stimuli that were sensed at any given moment and associated in time through synaptic tagging. Thus, LTP is an excellent candidate for the molecular substrate of the memory formation process for three reasons:

(1) LTP represents plasticity in the brain’s cerebral cortex that can change with experience in response to new stimuli.
(2) LTP is long lasting.
(3) LTP allows for the association of multiple stimuli.

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[301] Frey and Morris, 1997
[302] Nadel, 2008

When considering that each neuron receives 1,000 to 10,000 inputs from other neurons classical conditioning research and molecular synaptic plasticity findings have served as the foundation of modern artificial neural network theory. Indeed, modern artificial neural network theory attempts to extend such a model's ability to predict complex behavioral phenomena by focusing on associations formed within huge networks of simultaneously activated neurons (i.e. as opposed to focusing only on changes at individual neuron-to-neuron connections in isolation).[303] Additionally, artificial neural network researchers have attempted to precisely quantify the mathematical relationships associated with changing neural connections to both explain and simulate the processes of learning and decision-making based on prior learning.[304] Because of the huge number of neural connections, dynamically changing neural connectivity patterns have required computers to model. The power of such simulations to model human behavior depends on the mathematical formula used to adjust the strengths of various neural connections.

One of the most influential equations describing neural plasticity-based learning is the delta rule.[305] To describe the delta rule, consider the previously discussed classical conditioning scenario that is summarized in the diagram below.

[303] Lieberman, *op. cit.*, pg. 479.
[304] *Ibid.*, pg. 479.
[305] *Ibid.*, pg. 479.

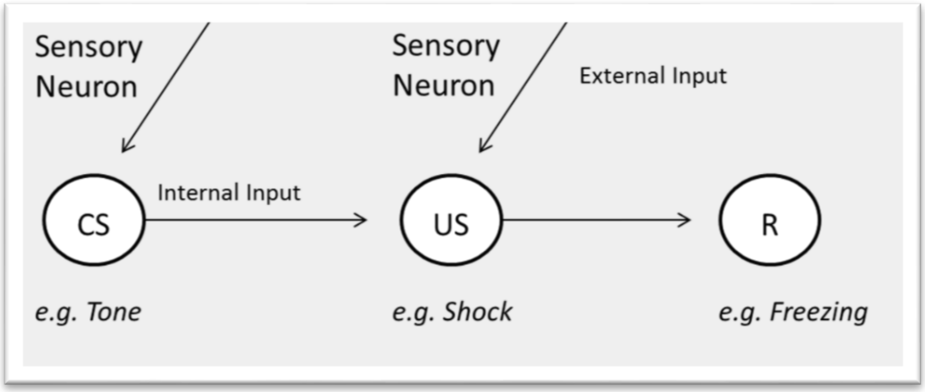

Figure 13: Neural Substrate of Simple Classical Conditioning: *This diagram summarizes the basic interactive components of a conceptual biological neural network. The circles represent neurons, and the arrows represent neural connections. The CS and US neurons are both activated by sensory neurons that detect stimuli from the external environment. The CS→US connection represents an internal connection because CS-induced activation of the US neuron indirectly originates from external sources.*

Initially, when a rat detects electric shock, a sensory neuron activates the US neuron, which activates the R neuron, which initiates the freezing behavioral response. In this case, the sensory neuron signaling the presence of electric shock is considered the US neuron's external input because this input source directly signals an event that was sensed from the environment. If auditory tones have been reliably paired with the presentation of shock, then the connection between the CS and US neurons will strengthen to the extent that activation of the CS neuron alone will produce subsequent activations of the US and R neurons, thus eliciting the freezing response. CS input into the US neuron represents an internal input because the input is originating from within the neural network (as opposed to the environment). According to the delta rule, each time the CS and US neurons are simultaneously active, "the change in the internal connection between two neurons (ΔI) is proportional to the difference between the internal and external inputs."[306] In other words:

$$\Delta I = c\cdot(\text{external input} - \text{internal input})$$

[306] Lieberman, *op. cit.*, pg. 481.

where *c* is some constant.[307]

Thus, in a naïve neural network, new associations are initially learned quickly after only a few associations, followed by a period of gradual, slow refinement of connective strength. Ultimately, the connectivity between two neurons will be at their strongest when the connective strength of the internal input is equal to the connective strength of the external output. At this point, no additional associations will have any impact on connectivity. In the previous example, this is the point when the tone would acquire the ability to produce the freezing behavior as strongly and reliable as the detection of electrical shock. Note that the learning process will slow down as the difference between the internal and external inputs decreases.

Interestingly – and perhaps not surprisingly – although the delta rule models the mathematical relationship of neural connection plasticity believed to underlie learning and behavioral responding, the rule strongly resembles mathematical models independently developed to describe associative learning in psychology research. Of particular note is the Rescorla-Wagner model of associative learning, which has remained influential over the past several decades.[308] In this model, the strength of a CS-US association is dynamic and can change as a function of each new CS-US temporal pairing. Just like the delta rule, a fundamental construct of the model is "associative strength." The degree to which the CS-US connection is strengthened after each pairing is expressed as:

Equation 1: $$\Delta V_{N} = \alpha\beta(\lambda - V_{N-1})$$

And current total associative strength of a CS after each CS-US pairing is expressed as:

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[307] *Ibid.*, pg. 481.
[308] Rescorla and Wagner, 1972.

$$\text{Equation 2:} \qquad V_N = \Delta V_N + V_{N-1}$$

ΔV represents the amount of learning that occurs as a result of a given CS-US pairing. V represents current cumulative learning to the CS (current associative strength). α and β are fixed learning rate parameters analogous to salience of the CS (α) and intensity of the US (β). λ represents the total amount of learning that can be supported by a given US. According to the model, there is a limit to how much associative strength a given US can support (specified as λ). Thus, each CS-US association produces some new knowledge (ΔV) and consequently total current knowledge increases (V). However, this increase will continue only so far because there is a limit on total knowledge that can be acquired in a given situation (λ). When the current total learning (current value of V) becomes equivalent to asymptotic associative strength that can be acquired in that situation (value of λ), learning stops and further CS-US pairings will not produce any new learning. This occurs when the value of V reaches the value of λ. When this happens, the parenthetical term ($\lambda - V_{N-1}$) will equal zero and no further learning can occur. Equation 1 functionally reads as "how much associative learning will be incremented on pairing N is determined by how much can be learned, minus what has been learned so far." Equation 2 functionally reads as "current total learning at the completion of pairing N is equal to the amount of learning that occurs on pairing N plus the total learning accumulated before pairing N occurred."

Thus, the delta rule developed independently in neural network research resembles mathematical models of associative learning in psychology research. Both models place great emphasis on the belief that learning/neural changes initially occur rapidly before slowing down and eventually stopping. In both cases, this process is a function of prior learning. In the Rescorla-Wagner model, learning ultimately stops because the organism has successfully learned all it can about a given stimulus. According to the delta rule, a neural connection stops strengthening because the internal input has "learned" that it identically represents the external input with regards to producing a behavioral response. To translate this to our classical conditioning example, synaptic plasticity stops because the organism has learned that it should respond equally to the detection of a tone or a shock. The fact that these two mathematical models so closely align provides credibility that they actually describe the same process from two different angles. The Rescorla-Wagner model accurately represents associative learning at a behavioral level, the delta rule describes the dynamics of changes in neural connections underlying behavioral learning, and extensive biological research in long term potentiation (LTP) provides a detailed molecular mechanism demonstrating exactly how changes in strength between neurons occurs to accommodate learning processes and appropriate behavioral selection processes in biological neural networks.

Given our significant recent inroads in scientific understanding unifying aspects of learning, behavior, and dynamically changing biological neural circuitry connections, the eventual development of artificial intelligence that can simulate human-like cognitive functions seems plausible. To this end, McClelland and Rumelhart conducted research on distributed information processing using an artificial neural network [computer model] containing thousands of neurons to demonstrate that simple neural networks could form "concepts," which are abstractions that require the combination of several different memories to construct. For example, recognition of a dog would be a concept, as a dog is composed of numerous features, such as a tail, legs, fur, and ears. This research effectively extends the Rescorla-Wagner model beyond the scope of modeling only a few neurons at once.[309]

[309] McClelland and Rumelhart, 1985.

A brief description of artificial neural network organization is presented here to give the reader a working knowledge of how these networks can support complex information processing, although this description will avoid detailed technical complexities. According to McClelland and Rumelhart, an artificial neural network is governed by many properties.[310] First, the artificial neural network is composed of simple, highly interconnected ***units*** (analogous to neurons) that "take on activation values, and communicate with other units by sending signals modulated by weights associated with the connections between the units."[311] Each weight can have an activation value of any real number ranging from -1 to 1, with a *negative* weight signifying that the activation of one unit would *decrease* the probability that units receiving its output would fire. The closer to -1, the more statistically unlikely such connected units would form an activation chain, and vice versa. In other words, weights are simply mathematical abstractions that simulate changes in voltage strength between two neurons in biological neural networks. Each unit may represent a basic memory, sensory input, or a complex concept that is activated by receiving simultaneous inputs from activated units representing the concept's constituent parts (e.g. units coding for ears, fur, legs, etc.). Alternatively, simple representations, such as the color of an object, might be encoded in a distributed pattern of activation from many units throughout the network.

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[310] *Ibid.*
[311] *Ibid.*

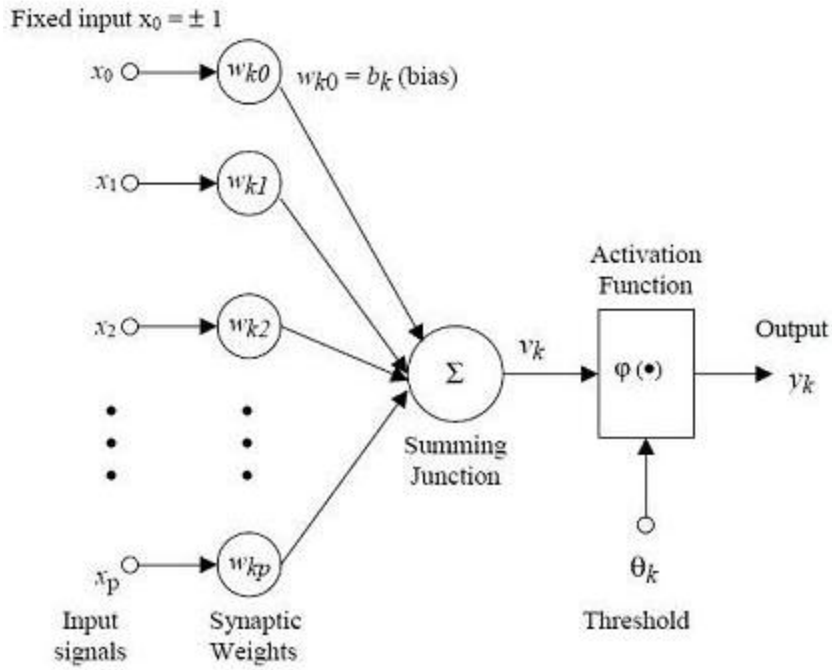

Figure 14: Single Unit Activation: *Input signals originate from upstream units within the network. The strength of these inputs is modified by mathematical synaptic weights, thus calibrating the individual input strengths as a function of their importance on each downstream unit. All calibrated inputs are summed at the downstream unit (summing junction). If the summed product is greater than a threshold value, then an output value is produced, which serves as an input to the next downstream neuron within the network.*

Picture Source: http://www.learnartificialneuralnetworks.com/#Mathematical

$$v_k = \sum_{j=1}^{p} w_{kj} x_j$$

Figure 15: Summation Junction Algorithm: *This algorithm represents the mathematical expression for summing a unit's weighted inputs (summation junction) when determining the unit's output.* V_k *represents the summation value (i.e. activation value),* w_{kj} *represents the weight associated with input j, and* x_j *represents the raw value of input j. See Figure 14 for the illustrative representation of these relationships.*

Picture Source: http://www.learnartificialneuralnetworks.com/#Mathematical

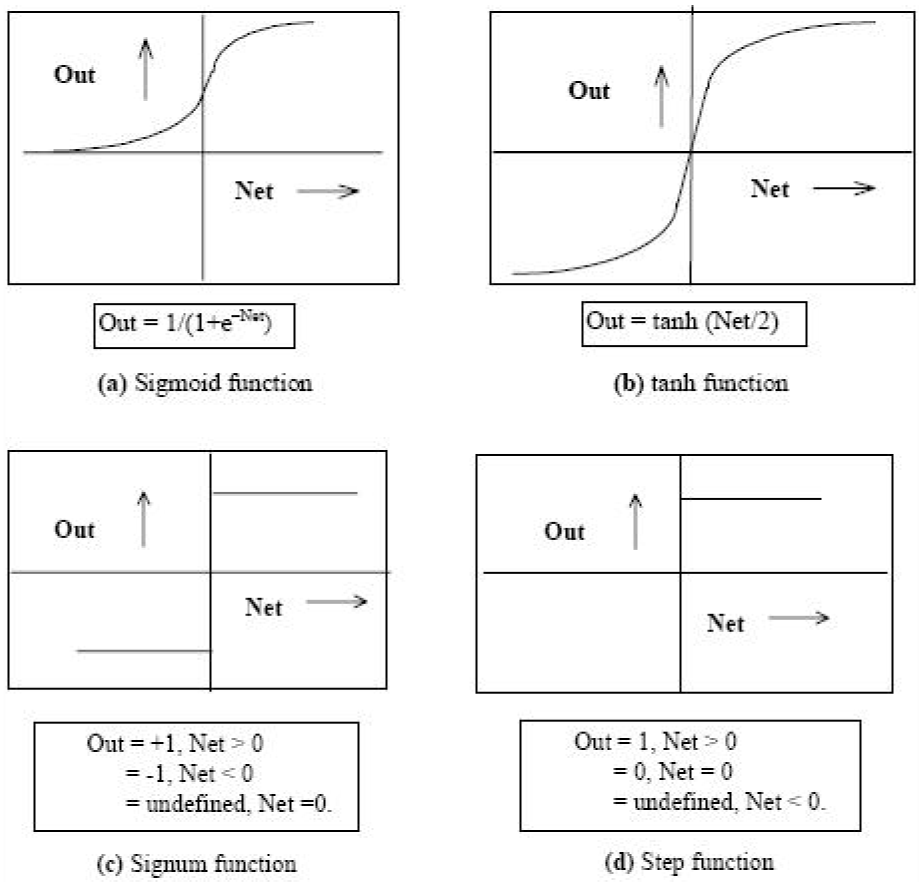

Figure 16: Possible Unit Output Values: *Output values generally range from -1 to 1, and they can represent continuous or step functions. In other words, a range of summed values can be mapped to a single output value, or the summed value can be the output value.*

Picture Source: http://www.learnartificialneuralnetworks.com/#Mathematical

An artificial neural network is assumed to have modular organization of the constituent units, with each module connecting to other models via inputs and outputs. According to McClelland and Rumelhart, the "state of each module represents a synthesis of the states of all of the modules it receives inputs from. Some of the inputs will be from relatively more sensory modules, closer to the sensory end-organs of one modality or another. Others will come from relatively more abstract modules, which themselves receive inputs from and send outputs to other modules placed at the abstract end of several different modalities."[312] Thus, the artificial neural network's "mental state" is a reflection of the precise constellation of units and modules that is activated at a given moment. Information processing represents the dynamic changes from one mental state to another. In such a system, knowledge is represented by the mathematical values of the *weights* (see Figures 14 and 15) governing each unit's activation within an activation chain, as these values allow patterns of activation to be reliably recreated and accessed when faced with the same inputs originating from within the network and from the environment. Because the weights represent the strength of each inputs' influence on a downstream unit's output, these weights numerically encapsulate which relationships are meaningful within the network.

If knowledge represents the mathematical weights governing the dynamics of network activation, then learning and memory involves the adjustments of specific weights to capture traces of previous pattern activations using the delta rule described earlier so that these network activations can be easily and reliably recreated.[313] For example, if the weight value between unit A and unit B is 0, then no meaningful connection exists between these units, regardless of unit A's input value to unit B. Unit A's input will be multiplied by the weight (which is 0), thus rendering the input insignificant in the summing junction. Consequently, the connection would not be included in the functional network in which unit B is embedded.

If, through the process of learning, the network recognizes that unit A and unit B have a meaningful connection, the weight value is positively adjusted in accordance with the delta rule, thus allowing unit A's input to meaningfully contribute to unit B's activation. Weight adjustment occurs "to make the internal input to each unit have the same effect on the unit that the external

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[312] *Ibid.*
[313] *Ibid.*

input has on the unit. That is, given a particular pattern to be stored, we want to find a set of connections such that the internal input to each unit from all of the other units matches the external input to that unit."[314] With appropriate weight tweaking, mental states and knowledge acquired from the external environment can be independently reproduced by the internal network at times and places absent of any original environmental context.

Figure 17: Representation of Learning in a Simple Neural Network: *This diagram explores the role of weights in defining the activation relationship among units (i.e. neurons) within a simple network.*

In the Pre-Training diagram, notice that the Sensory Neuron→US Neuron connection and the US Neuron→R Neuron connections have a weight of 1, meaning that these neuron pairs are as tightly coupled as possible. In both cases, activation of the input neuron will subsequently produce activation of the output neuron so long as the output neuron receives input from only one neuron (as is the case in this example). The CS Neuron→US Neuron has a weight of 0, meaning that the CS Neuron is currently neutral; its activation has no impact on the subsequent activation of the US Neuron.

In the Post-Training diagram, classical conditioning has occurred to the point where the presentation of a tone produces the freezing behavioral response. Notice that this learning has been encapsulated by the change in weight between the CS Neuron→US Neuron, which now has a value of 1. This new value indicates that the network has learned that the tone (CS Neuron) reliably predicts the onset of shock, subsequently adjusting the weight to reflect this newly-discovered tight coupling. Future presentations of the tone alone will now activate the US Neuron, thus creating a CS Neuron→US Neuron→R Neuron activation chain.

McClelland and Rumelhart trained such an artificial neural network to accurately distinguish dogs and cats from each other by training the network to recognize and synthesize the constituent parts

[314] *Ibid.*

of each animal to produce the recognition.[315] For example, the activation of each unit within the network was sensitive to a dog's specific feature, including its tail, legs, fur, and ears. To increase recognition flexibility, the network was trained to recognize dogs by showing it dogs that had three of these typical features along with an atypical feature (e.g. a dog might have short legs). After each presentation, the units coding for the typical features would be reliably activated most of the time across the 50 training presentations, and thus these units would become tightly coupled. Perhaps the study's most interesting finding is that the network could recognize new dogs that the network had never been exposed to before, indicating that the artificial neural network could accurately make generalizations to novel situations based on prior experience.[316] In this study, the network was able to generalize because the new dog had some features that were typical to all dogs. The units coding for these typical features successfully activated the constellation of units that encode all of a dog's features through the tight coupling of these units during training, thus allowing the network to recognize the new dog. The network's generalization was robust, even when it was trained to recognize dogs and cats, both of which share many features in common.[317]

The ability to train artificial neural networks through examples is among its most attractive features. Given the nearly infinite number of potential mental states and decisions required to operate in real world environments, hard-coding autonomous robots to appropriately handle all possible situations is impractical, at best. In addition to the impossibly long and complex code required for such an approach, programmers would be unlikely to know how to respond in every possible potential situation, themselves. Thus, artificial neural networks are a superior solution

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[315] *Ibid.*
[316] *Ibid.*
[317] *Ibid.*

because they enable an artificial intelligence that is specifically designed to learn from previous experience and adapt future behavior accordingly, even in novel situations.

Although this approach is designed to emulate the superior learning capabilities of biological systems, artificial neural networks are not constrained by many of the limitations inherent in biological systems. For example, robots never get bored or tired, and they will continue to fine-tune any necessary training exercises for as long as necessary. Additionally, all knowledge learned through the diligent training of one robot can be directly uploaded into all other robots of the same type. Thus, only a small number of robots are needed to establish the appropriate weights for any desired number of robot clones. Training is greatly expedited because feedback from real life operations can be immediately incorporated into all similar robots, despite the fact that they did not experience the situation firsthand. Lastly, if a robot makes a decision that humans deem to be a mistake, algorithms exist for isolating the units most responsible for the error within extremely complex artificial neural networks and adjusting their weights accordingly to prevent repeat offenses.[318]

Examples already exist of such successful training strategies. As was noted earlier, Stanley – Stanford's winning submission in the 2005 DARPA Grand Challenge – was trained by incorporating the decisions of its early human drivers into its own decision-making process, thus tremendously reducing its error rate. Instead of wasting time trying to hard-wire Stanley to handle all possible driving scenarios, the Stanford team *showed* Stanley how to drive.

[318] For a detailed explanation, see Luger, 2009, pg. 467

Other examples of such artificial learning include adaptive quadrotors, which are 4-bladed helicopters that could fit in one hand, that learn to maintain steady flight while resisting the wind.[319] At first the quadrotors are not very good at this task, but after several training runs, they quickly learn to make the appropriate adjustments. Similar to McClelland and Rumelhart, researchers at Cornell's Personal Robotics Laboratory are teaching robots to recognize categorical groups of objects based on their features.[320] Researchers in Switzerland have developed robots with artificial neural networks that not only learned how to find food, but also learned to hide their visual signals from other robots to avoid sharing the food with them.[321] Thus, training of the artificial neural network yielded an adaptive social phenomenon that was not explicitly hard-coded.

Future UAVs could be trained to execute their missions in ways similar to these examples. For example, the Predator UAV's 950,000 hours of flight has produced countless hours of sensor data.[322] A subset of this data could be converted into a training package for all UAV aircraft that have similar sensor payloads and execute similar missions, such as ISR and lethal strike. Similar to how Stanley was trained by observing and learning from examples of human driving, UAVs could use this training package of human remotely-piloted missions to learn how humans executed the missions. Additionally, all UAV artificial intelligence could continuously observe and learn from ongoing remotely-piloted UAVs while autonomy is slowly phased into UAVs. If an autonomous UAV commits an error, mathematical algorithms can be used to determine the source of the error and correct it.

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[319] Ackerman, September 12, 2011
[320] Ackerman, September 07, 2011
[321] Mitri, Floreano, & Keller, 2009.
[322] Beidel, *op. cit.*

In summary, for UAV autonomy to successfully handle extremely complex, high-stakes environments requiring appropriate dynamic behavioral adjustments and generalizations when facing novel situations, a strong case can be made that artificial intelligence should be modeled on the human's biological neural network system because it is already well-designed to learn and perform such tasks. Psychological and biological research into the nature of the human nervous system has identified biological design and operation features that should be emulated in artificial intelligence systems for UAVs. Artificial neural network research demonstrates that existing software models can be used to provide UAV autonomy with human-like learning and information processing capabilities. In fact, IBM's recent advances in hardware have created computer chips that functionally resemble biological neurons, thus allowing artificial neural networks to capitalize on physical architecture to achieve parallel processing capabilities never seen before.[323]

Although current research falls short of producing artificial neural networks that can match humanity's decision making and information prowess, the fact that technology is advancing at an exponential rate suggests that such ability will occur faster than expected. When asked to estimate the date when humanoid robots would be introduced into combat situations in an infantry role, a survey of scientists predicted 2020.[324] Experience with these autonomous ground robots is indicative of similar challenges regarding the development of artificial intelligence for UAVs. This predicted capability is only 8 years in the future, and although the projection could be way off, the previously described research on exponential trends suggests that they could well be *overestimating* the time required to develop the necessary technology.

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[323] Gross, *op cit.*
[324] Singer, *op. cit.*, pg. 130

2.3 **Outlining a Future Strategic Vision for Autonomous UAVs**

So far, the UAV's history as a remotely-piloted ISR and strike platform has been reviewed. Additionally, the advantages and challenges of current UAVs have been explored, along with a potential artificial intelligence model for achieving future UAV autonomy. However, the basic question remains: given the potential legal and ethical problems, why should UAV autonomy be pursued and favored over the successful, existing system of remotely-piloted UAVs?

At first glance, discussions of armed, autonomous robots frequently invite popular culture jokes or outright dismissal. In casual conversations, the subject frequently invokes images of Terminators attempting to annihilate their human creators. In more serious conversations, both leading industry and military leaders have expressed serious doubts regarding the feasibility and likelihood of UAV autonomy. For example, U.S. Air Force captain Patrick Eberle noted in the *Air and Space Power Journal* that "[in] some cases, the potential exists to remove the man from harm's way. Does this mean there will no longer be a man in the loop? No. Does this mean that brave men and women will no longer face death in combat? No. There will *always* be a need for the intrepid souls to fling their bodies across the sky."[325] Military expert Eliot Cohen echoed this sentiment when he observed that "people will always want humans in the loop."[326] When asked about the potential for arming autonomous robots during an interview, Helen Greiner of military robot manufacturer iRobot reportedly replied that such a scenario was so far in the future that she did not "see it as an issue."[327] Robert Quinn, vice president of military robot manufacturer

[325] Eberle, 2001
[326] Singer, *op. cit.*, pg. 123
[327] *Ibid*., pg. 124

Foster-Miller, refuted the notion of armed autonomous robots more forcefully when he stated that man remaining in the loop was a "line in the sand."[328]

However, not everyone agrees with such absolutes. Military technology expert Noah Shachtman observed that such blanket statements more closely resembled brainwashing than analysis.[329] Additionally, Shachtman noted that people are generally uncomfortable with the fact that the military is outsourcing its core competencies to robots, and that the detractors' adherence to outright dismissals of armed, autonomous robots "helps keep people calm that this isn't the Terminators."[330]

The continuing appeals to science-fiction reveal an inherent skepticism that humanity can advantageously and appropriately harness military robots. On the contrary, the rise of autonomous UAVs promises to introduce many key future tactical advantages. Specifically, autonomous technology will allow the U.S. Air Force to better leverage UAVs for large-scale ISR and strike purposes, thus adopting and expanding the successful small-scale UAV model established by the CIA since 2001. The next sections will explore the challenges that the U.S. Air Force is currently facing in counterinsurgency and irregular warfare conflicts, as well as strategic vision for employing future autonomous UAVs to meet this challenge. The discussion will address the following points:

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[328] *Ibid.*, pg. 124
[329] *Ibid.*, pg. 124
[330] *Ibid.*, pg. 124

- The U.S. Air Force's effectiveness in the War on Terror is being increasingly questioned because of the potential for lethal airpower to undermine public support abroad and because of the U.S. Air Force's lack of a tactical reconnaissance aircraft.
- Autonomous UAVs will provide a new set of tactical advantages outlined by the U.S Air Force within their 2047 timeframe that will provide tactical reconnaissance and discreet lethal strike capabilities desperately lacking in current arsenals.
- In a time of defense spending cuts for the foreseeable future, autonomous UAVs will reduce the military's financial burden by significantly reducing the number of personnel and resources associated with human piloted aircraft and non-autonomous UAV "logistic tails."

2.3.1 The United States Air Force's Identity Crisis in Counterinsurgency Conflicts and Irregular Warfare

For the past five or six decades, the U.S. Air Force has been equipping itself to fight a nuclear nation-state of equal skill and technological prowess. This mindset is encapsulated in the U.S. Air Force's capstone operations publication – titled Air Force Doctrine Document 2, Operations and Organization – which emphasizes high intensity kinetic operations.[331] During the Cold War, the U.S. Air Force has been designing its weaponry and strategic doctrines to counter the Soviet Union. Recently, the emergence of China as a potential adversary has likely compelled the U.S. Air Force to continue investing in extremely expensive, state-of-the-art warplanes, such as the Lockheed Martin's $143 million F-22 Raptor.[332] Indeed, Lockheed Martin's F-22 webpage touts the Raptor's advanced stealth, maneuverability, and air dominance.[333]

However, there is one problem: this bank-breaking warplane is virtually useless in the 10-year War on Terror, in part because the enemy forces do not have warplanes and tend to avoid conventional battles. In 2007, tensions mounted within the military ranks when then-Secretary of Defense Robert Gates expressed his belief that future conflicts would represent small, asymmetric wars that would not feature the Air Force's capabilities.[334] Additionally, Gates singled out the F-22 Raptor as an expensive Air Force system that had almost no role in the War on Terror.[335] Gates further reprimanded a top U.S. Air Force official for "borderline insubordination" after the

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[331] Moseley, 2007
[332] Ferran, 2011
[333] See http://www.lockheedmartin.com/us/products/f22/f-22-capabilities.html
[334] Schachtman, *op. cit.*
[335] *Ibid.*

general informed him that he planned to purchase twice as many F-22s as had been authorized, directly violating Gates' orders.[336]

This showdown mirrors the 1949 "Revolt of the Admirals" incident when three U.S. Navy admirals were fired over a disagreement regarding resource appropriation between the construction of a new class of supercarriers (the USS *United States*) and long-range nuclear bombers.[337] At that time, resource allocation for supercarriers exemplified "business as usual" for the military and represented another instance in which military planners sought to adopt current equipment and practices for the new (nuclear) age. As retired U.S. Air Force Colonel John Jogerst succinctly asks, "[is] the F-22 our *United States*, or will we shift our priorities to build needed capabilities for [irregular warfare]?"[338]

The U.S. Air Force's desire to defy orders and purchase hugely expensive hardware that only has limited utility in today's conflicts is representative of a larger U.S. Air Force institutional identity crisis, causing many defense analysts to openly question the need for technologically advanced warplanes altogether.[339] This skepticism likely stems from the fact that military operations have recently been expanded to encompass many additional missions beyond the kinetic operations outlined in the Air Force Doctrine Document 2, to include "humanitarian assistance, disaster relief, counterinsurgency (COIN), unconventional warfare (UW), and theater-security cooperation with partner nations."[340] In other words, the U.S. Air Force is attempting to misapply

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[336] *Ibid.*
[337] Jogerst, 2009
[338] *Ibid.*
[339] Moeller, 2010
[340] *Ibid.*

its doctrine of kinetic, conventional strikes to UW and COIN settings, such as Iraq and Afghanistan.

Consequently, the U.S. Air Force needs to update its written doctrine and practices to reflect detailed, flexible plans outlining its strategic considerations for an eclectic array of future conflicts. Given China's rising military power, Russia's strategic modernization, North Korea's currently uncertain political future, and Iran's increasingly adversarial posturing, such doctrine cannot abandon conventional and nuclear warfare planning. However, despite its inability to predict the need for a robust COIN strategy in Iraq and Afghanistan, U.S. Air Force planners still believe that such situations will not occur again.[341] The U.S. Air Force has neglected political and budgetary issues associated with long-term involvement in unconventional conflicts.[342] Additionally, the U.S. Air Force has given little thought to a viable exit strategy regarding the training and equipping of a destabilized country's military.[343] In a 2011 piece published in the *Air and Space Power Journal*, Thomas Rath summarizes this situation when he notes that the "[U.S. Air Force] has so distanced itself from the realities and demands of [irregular warfare] that it has no awareness – much less understanding – of the critical role that airpower must play…."[344] Retired U.S. Air Force Colonel John Jogerst further clarified the U.S. Air Force's position when he observed that it had dismissed UW as the "last war" and was calling for an "all-out push for modernization to prepare for war with a technologically sophisticated peer or near-peer - enemy."[345]

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[341] Jogerst, *op. cit.*
[342] Rath, *op. cit.*
[343] *Ibid.*
[344] *Ibid.*
[345] Jogerst, *op. cit.*

Recent historical evidence underscores a persuasive and urgent need for the U.S. Air Force to formally determine how to best support unconventional conflicts. To wit, none of the 14 major global conflicts during the summer of 2008 were conventional in nature.[346] Only 4 of the roughly 30 major conflicts from 2000-2009 were fought between nations.[347] A 2007 RAND report identified eight regions that are not controlled by a recognizable government, thus potentially representing ideal terrorist safe havens.[348] Recently, Sudan, Sri Lanka, Colombia, the Philippines, and notably Venezuela and Nigeria – two of the largest U.S. oil suppliers – have experienced unconventional conflicts.[349] Combined with the plethora of potential future global destabilizations, the U.S.'s decade of UW conflicts within Afghanistan, Iraq, Pakistan, and arguably Libya highlight the fact that the U.S. has been heavily involved in UW and COIN operations in recent years and will likely continue to be involved for the foreseeable future.

To successfully participate in UW and COIN operations, the U.S. Air Force must identify its set of core competencies that uniquely address the special objectives of these conflicts. Regarding important COIN campaign features, retired Royal Air Force pilot Paul Smyth notes that "there is broad acceptance of principles such as the primacy of politics in a COIN campaign and the need for a political aim, the imperative for a coordinated pan-government approach, the importance of intelligence and information, the effective separation of insurgents from their base of support, the neutralization of the insurgent, the need for long-term postinsurgency considerations, and the need to protect the population."[350] In other words, COIN campaigns differ from conventional conflicts in that COIN campaigns feature a legitimacy-seeking clash of ideals that is fought for the hearts and minds of innocent civilians. Consequently, the ultimate goal is inherently political,

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346 *Ibid.*
347 *Ibid.*
348 Rabasa et al., 2007
349 Jogerst, *op. cit.*
350 Smyth, 2011

as physical security is but one of many possible issues that are important to a given population. For example, the withdrawal of visible U.S. military presence could be the population's desired goal.

For terrorist groups like al Qaeda, having public support is extremely important for several reasons. Because the terrorists cannot defeat the U.S. military in a conventional fight, the secrecy of terrorist movements and activities is paramount to their success.[351] Obtaining such secrecy necessitates blending in with the civilian population. This secrecy is continuously preserved to the extent that the public sympathizes with the terrorists' ideology and chooses not to reveal the terrorists' identities or locations to the U.S. military. Al Qaeda learned this lesson all too well when it alienated local Iraqi citizens by carrying out a series of brutal decapitations.[352] Thus, to obtain and maintain widespread support, recruits, and resources, terrorists must continue to ensure that their message is receiving media attention by regularly engaging in psychological deception and shocking acts of violence that are carefully tailored to avoid hurting the terrorists' perceived constituency among the local population.[353] As an example of deception, al Qaeda has sought to draw parallels between the U.S.'s involvement in Afghanistan with the Soviet Union's invasion of Afghanistan, thus highlighting a scenario in which the U.S. could collapse under the economic burden of maintaining a costly war within the country in the same way that the Soviet Union collapsed shortly after leaving Afghanistan.[354] Rightly or wrongly, such a parallel would be useful for al Qaeda because it creates the perception for its followers that the group is capable of defeating world superpowers. Additionally, al Qaeda attempted to use the U.S. invasion of Iraq to rally support by using its publications to argue that the U.S. was aggressively attacking

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[351] Rath, *op. cit.*
[352] Benson, 2011
[353] Hoffman, 2006, pg. 290
[354] *Ibid.*

Muslims, and that al Qaeda was a protector of the faith.[355] Thus, in a conflict where perceptions are reality, Dr. Mark Clodfelter – a professor of military strategy at the National War College – summarizes this strategy by observing that the skilled insurgent “will work hard to paint his cause in a positive light and to cast his enemy’s efforts as evil.”[356]

Because the sympathies and allegiances of the local citizenry are of such great importance in determining the ultimate success of insurgencies and terrorist activities, the U.S. military must also ensure that its actions do not alienate the population, lest it increase support for the opposing forces. This point is the reason that the U.S. Air Force’s powerful airstrikes have frequently backfired in spite of achieving the desired tactical goals of their use. Although kinetic power serves a useful purpose in UW by destroying insurgents who pose a danger to the military and civilians, such strikes can anger the local population when innocent citizens are accidently killed. Such a scenario was outlined earlier in this work regarding how civilian casualties resulting from UAV strikes in Pakistan may have had the unintended consequence of rallying the local population against the U.S. and increasing recruiting and support for al Qaeda and the Taliban. Consequently, multi-year airstrike campaigns fueled by open-ended political goals “play directly into the insurgent’s hand and intensify the likelihood that he will wage a sporadic guerilla war that the American air power is ill equipped to obstruct,” thus sustaining the insurgency indefinitely.[357]

Although any type of military operation may produce unintended civilian casualties, such accidents resulting from airstrikes preferentially receive the most media exposure, thus giving the

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355 *Ibid.*, pg. 291.
356 Clodfelter, 2011
357 Clodfelter, *op. cit.*

U.S. Air Force a smaller margin of error in COIN campaigns.[358] In Afghanistan, civilian casualties from airstrikes have defined public, media, and political perceptions associated with their use despite the fact that only a small fraction of air sorties have ever produced any civilian casualties.[359] Such accidents clearly damaged the overall COIN campaign in Afghanistan by undermining popular support for the U.S.-led alliance.[360] Thus, it is entirely possible that these rare collateral damage incidents have actually *increased* the overall number of militants actively opposing U.S. forces in both Afghanistan and Pakistan by compelling some fraction of the militant's passive supporters to take up arms against the United States.

Despite these drawbacks, kinetic airpower remains a staple capability for the U.S. Air Force in any conflict, and military officers cannot be expected to eschew airpower if U.S. servicemen are attacked or if a high-value militant leader has been located. In fact, heavily-controlled airpower serves a crucial role in the current Afghanistan conflict.[361] The real challenge is determining how the U.S. Air Force can effectively incorporate airpower in COIN and UW conflicts without undermining the military's strategic goals. Ideally, achieving such goals begins by acquiring the capabilities needed to separate militants from the general population and/or apply lethal force to militants without producing collateral damage. Given the fact that the public's perceptions regarding U.S. airpower are just as important as the physical consequences of any airstrike, an important secondary requirement is that the lethal force's visibility should be minimized to the greatest extent possible to avoid instilling negative perceptions in the local population regarding the U.S.'s intents and capabilities. Most importantly, achieving these goals requires mobility and

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[358] Smyth, *op. cit.*
[359] *Ibid.*
[360] *Ibid.*
[361] *Ibid.*

robust ISR capabilities that allow enemy forces to be located, watched, and struck at a time and place that minimizes collateral damage.[362]

Despite their recent utility in COIN and UW conflicts, current UAV usage fails to fully achieve these goals for several reasons. Larger UAVs, such as the Predator, are ideal surveillance tools for observing a specific target for an extended period to determine the target's pattern of life, which can be used to forecast the best moment to strike the target without endangering civilians. However, such success often overshadows the fact that UAVs have very little ability to perform reconnaissance because they frequently cannot be used to monitor situational awareness due to their reliance on high-magnification cameras which limits their field of view.[363] Alternatively, smaller hand-held UAVs, such as the Raven, are ideal for very short range reconnaissance.[364] In either case, technical limitations dictate that UAVs must first be directed to their targets by vulnerable, relatively immobile ground assets before they can perform their respective surveillance or reconnaissance missions.[365]

Even if UAVs could locate enemy forces unaided by ground assets, they would have great difficulty surprising the enemy. Many of today's commonly-used UAVs have extremely noisy propellers because their designs do not optimize sound reduction practices.[366] Thus, militants do not need special equipment to know when a UAV is approaching; they can quickly run for cover whenever they hear one approaching. This limitation carries considerable importance because

[362] Rath, *op. cit.*
[363] *Ibid.*
[364] Schneider, *op. cit.*
[365] Rath, *op. cit.*
[366] Chavanne, 2009

sound is the primary signature sensed by people on the ground, thus rendering noisy ISR/light attack platforms ineffective.[367]

Lastly, the recent incidents of insurgents hacking into UAV control feeds using cheap off-the-shelf software illustrate another UAV vulnerability. Although military officials have indicated that these feeds have now been encrypted to prevent insurgent interception, the very fact that insurgents can still detect the presence of feed signals using simple portable receivers provides them with valuable information regarding the proximity of searching UAVs.[368] Thus, despite military-grade encryption, insurgents can still defeat these advanced technological systems by disappearing whenever feeds are detected for as long as UAVs continue to be remotely piloted from afar.[369]

Despite the UAV's many advantages, the combination of their shortcomings is significant for UW conflicts, in which the secrecy of militant movement is paramount for avoiding powerful U.S. conventional weapons. History indicates that militant tactical units are generally sufficiently small to avoid detection until they muster to attack.[370] To counter such guerilla tactics, the U.S. needs to invest in light reconnaissance assets that are suitable at *both* finding and surveying the enemy while being capable of carrying out small-scale, low-visibility precision strike capabilities. Such tactical reconnaissance assets should also be able to provide confirmation of strike result, flexible viewing ranges and angles, and high mobility.[371] Being largely unable to locate enemy targets unassisted, watch enemy forces secretly, and strike targets discreetly, UAVs do not

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[367] Rath, *op. cit.*
[368]*Ibid.*
[369] *Ibid.*
[370] *Ibid.*
[371] *Ibid.*

currently fill this needed tactical reconnaissance role. Illustrating this point is Boeing's inability to effectively provide UAV surveillance along the U.S.-Mexico border despite the fact that it is already several years into a multi-year contract to provide such a service. Such a scenario is significantly more tractable than searching for enemy combatants in a foreign land, as this program involves a combination of a clearly defined, well-mapped border and an uncontested area that is backed by a border fence and stationary video surveillance.[372]

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[372] *Ibid.*

2.3.2 Key Technology Enablers Supporting Future Autonomous UAVs

Continued investments in research and development supporting UAV autonomy and UAV miniaturization may ultimately allow UAVs to provide the missing tactical reconnaissance role sometime within the U.S. Air Force's 2047 timeline for UAV automation.[373] Regardless of whether the U.S. Air Force explicitly recognizes how autonomous UAVs can improve its standing in UW and COIN campaigns, recent Department of Defense and U.S. Air Force publications indicate that the U.S. military certainly understands the numerous advantages provided by future autonomous systems. For example, the *United States Air Force Unmanned Aircraft Systems Flight Plan 2009-2047* and the *FY2009-2034 Unmanned Systems Integrated Roadmap* provide a comprehensive overview of the future tactical considerations surrounding UAV usage.[374, 375] However, these documents do not provide a comprehensive overview regarding how these numerous tactical advantages interact with each other to produce an overarching strategic vision for the role of UAVs in COIN and UW settings; i.e., the "big picture."

Noel Sharkey, a professor of artificial intelligence and robotics at the University of Sheffield in England, recently observed that military robots are being deployed as quickly as they are made without any discussion regarding their development.[376] The implication is that near-term goals are dominating UAV development to such a large extent that a unified long-term vision is ignored. A second worrisome implication is that UAV use appears to be driven more by technology push rather than user pull. Indeed, when Peter Singer of the Brookings Institute was

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[373] Donley and Schwartz, *op. cit.*
[374] Clapper et al, *op. cit.*
[375] Donley and Schwartz, *op. cit.*
[376] Austen, *op. cit.*

reportedly asked by a senior defense department strategy expert about who was developing the strategy for UAV development and usage, Singer answered "everyone else thinks it's you."[377] This section will describe areas in which UAV autonomy is currently needed, outline desired future UAV tactical advantages, provide examples highlighting current progress towards these tactical goals, and offer analysis regarding how these autonomous capabilities will best fit together to support COIN and UW operations.

In many ways, future UAVs will represent a rapid departure from currently fielded UAV designs and capabilities. Today's UAVs feature medium-to-large high-altitude platforms that stalk targets previously identified by sources on the ground to cultivate a collection of intelligence that is sifted and processed over a period of time by analysts located in a distant place. Eventually, a decision is made regarding whether the target should be struck or abandoned in favor of a new quarry. Unfortunately, actionable intelligence becomes obsolete faster than ever in the information age.[378] Previous conflicts, featuring conventional forces whose relatively slow mobility and posturing generally allowed ample time to thoroughly review all relevant intelligence before choosing a course of action, have given way to networks of militants whose members are difficult to distinguish from civilians and who move so frequently that knowledge of their locations yesterday provides little information of their whereabouts today.

With so little time to act, the previously distinct tasks of intelligence gathering and intelligence analysis have become temporally compressed. The increasing speed of modern warfare will compel the U.S. Air Force to adopt UAVs that are designed to proactively search and hunt enemy

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[377] *Ibid.*
[378] Deptula and Francisco, 2010

forces by locating and anticipating their movements.[379] In adopting such a goal, the process of intelligence analysis will be pushed towards the tip of the spear, thus forcing intelligence analysts to become real-time participants in the hunt.[380] As UAV autonomy becomes refined and perfected, such real-time intelligence analysis will need to be implemented directly into the UAV's software, thus empowering the vehicle to rapidly make decisions on its own.

To achieve this vision of discreet, autonomous "hunter" UAVs that can locate, observe, and strike targets without alienating the local populace, numerous technology enablers must first be achieved to complement the development of the artificial neural network architecture that serves as the substrate for the advanced artificial intelligence. These enablers generally fall within three distinct groupings:

1. Development of Wide-Area "Smart" Sensors
2. Development of Micro UAVs
3. Development of Networked, Cooperative UAVs

[379] *Ibid.*
[380] *Ibid.*

2.3.2.1 Development of Wide-Area "Smart" Sensors

So far, this work has examined the feasibility of achieving UAV autonomy within the next few decades by considering the general exponential growth trend of technology and highlighting examples of increasingly autonomous robots within the past decade. Additionally, this work has described how biologically-inspired artificial neural networks are well-suited for appropriately sensing and acting in new and ambiguous environments in a manner that is influenced by a combination of dynamically-adjusted mathematical weights "learned" from previous experiences that are sensitive to outcome feedback. Lastly, autonomy's benefits for ISR missions were highlighted.

The current section extends the discussion by exploring the need for autonomous UAVs to redress manpower shortages engendered by current UAV technology. Additionally, this section explores how the development of wide-area "smart" sensors will help relieve this manpower strain in the short term by allowing UAVs to autonomously locate targets while enabling the long-term development of fully autonomous systems. If artificial neural network development represents the creation of a UAV's autonomous "brain," then wide-area "smart" sensor development represents the creation of a UAV's "sensory organs" that will help the autonomous brain make decisions through environmental monitoring and sampling.

In today's War on Terror, UAVs are arguably most heralded for their "costless" projection of military power without exposing friendly forces to danger. As was mentioned earlier, individual UAVs also carry a cheaper price tag than their manned-counterparts. Unfortunately, the full truth is that the UAV's cost – both in terms of manpower and price – is more complicated when the UAV's logistical tail is fully assessed.

First, the ability to remotely project military power via UAVs consequently creates a large need for subsequent intelligence analysis. Ever since September 11th 2001, the amount of hours the U.S. Air Force spends conducting ISR missions has increased 3,100 percent, with most of these missions being conducted by drones.[381] Throughout each of these missions, UAVs constantly maintain an active array of sophisticated sensors – including video, radar, and IR – that record and stream huge volumes of data back to ground bases. Each day, the U.S. Air Force must process and analyze nearly 1,500 hours of full-motion video, in addition to 1,500 still images.[382] To put this in perspective, U.S. UAVs transmitted 24 years of video stream in 2009, and this volume was expected to increase by a factor of 30 during 2011.[383]

Problematically, the requisite intelligence analysis functions needed to process this massive volume of data are still solely performed by (human) intelligence analysts, thus creating an information crisis.[384] To keep up with daily incoming data, 19 analysts are generally required to analyze the data for each drone.[385] During times of high operational tempo, a staggering 68 analysts are required for each Predator UAV.[386] Additionally, when including support staffs such as ground and recovery crews, a total of roughly 150 people is needed to execute each UAV operation.[387] Consequently, the U.S. Air Force has 65,000 to 70,000 analysts to process the

[381] Bumiller and Shanker, *op. cit.*
[382] *Ibid.*
[383] Weiss, 2011
[384] Bumiller and Shanker, *op. cit.*
[385] *Ibid.*
[386] Austen, *op. cit.*
[387] Mulrine, 2011

aggregate UAV data, with at least one review indicating that 100,000 analysts are currently needed.[388]

Contrary to popular perception, these numbers paint a clear picture: although UAVs remove humans from dangerous battlefields, they do not actually remove humans from war. Considerable manpower is still required to successfully execute meaningful campaigns that are physically undertaken by UAVs, and present trends indicate the situation will become much worse within the next few years. The U.S. Air Force is slated to purchase three new advanced sensor pods during the 2011-2014 timeframe that will significantly increase the amount of information that a Reaper UAV can transmit.[389] Billed as the "Gorgon Stare," this advanced sensor pod will supplement the preexisting high-magnification video camera now carried by Predator and Reaper UAVs.[390] Disagreement exists regarding exactly how many cameras are contained within the Gorgon Stare, with numbers ranging from 9 to 12.[391, 392] What is agreed upon is that the Gorgon Stare sensor pod will carry at least five electro-optical cameras for daytime footage and four IR cameras for nighttime footage, each positioned at a different angle.[393] These cameras are designed to provide a wide-area, low-resolution panoramic view of the landscape that the current high-magnification cameras do not provide, with images from individual cameras dynamically stitched together by a digital processer.[394] The Gorgon Stare can reportedly capture an area with a 4km radius.[395]

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388 Hill, 2012
389 Putrich, 2011
390 Whittle, 2010
391 *Ibid.*
392 Shachtman, 2009
393 Whittle, *op. cit.*
394 *Ibid.*
395 Hoffman, 2009

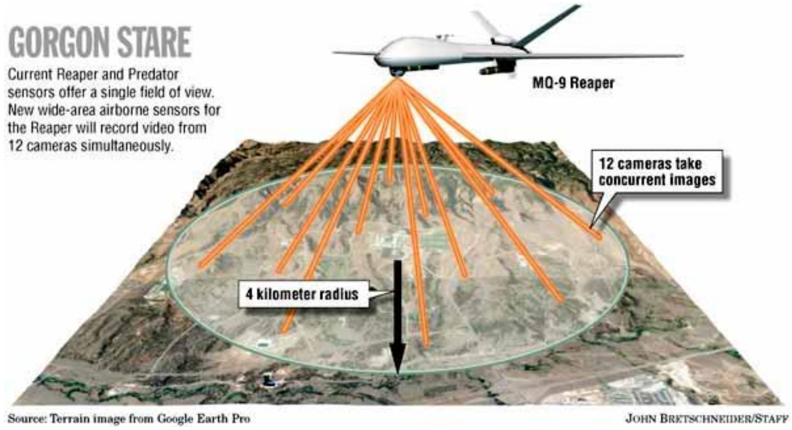

Figure 18: ***Gorgon Stare's Imaging Radius:*** *This image conceptualizes how the Gorgon Stare captures a panoramic image.*

Source: http://www.airforcetimes.com/news/2009/02/airforce_WAAS_021609/

The purpose of this wide-area view is to empower the UAV remote pilots to locate targets unassisted by ground assets at the target's location. Once a target is located, then the preexisting high-magnification camera can be used to acquire a detailed view. This method conceptually mirrors a biological eye's functionality in which highly distributed low-resolution peripheral receptors locate targets of interest, causing the eye's high-resolution fovea region to be turned towards the target to acquire additional, focused visual information. Additionally, U.S. Air Force officials hope that the Gorgon Stare will be useful in post-attack forensic analysis.[396] For example, if an IED explodes, analysts could review the Gorgon Stare's previously recorded panoramic video to reconstruct exactly how the IED was placed.

Perhaps unsurprisingly, the Gorgon Stare was beset with a number of technical shortcomings in its first round of testing that made it ineffective as a target locator.[397] Although the U.S. Air Force has reportedly corrected some of the issues, it will not currently provide a date which the

[396] Whittle, *op. cit.*
[397] Axe and Schachtman, 2011

Gorgon Stare will be operationally ready.[398] Assuming that this new sensor eventually works as planned, its use will significantly increase the information overload currently created by single full-motion video streams that are currently overwhelming large teams of intelligence analysts. Indeed, one report provided a staggering estimate that nearly 2,000 analysts would be needed to fully process the video stream from a single Gorgon Stare unit.[399] This figure does not account for the fact that significantly fewer UAVs would be required to watch a particular area, thus reducing combat air patrols and freeing up some analyst resources. However, the resulting personnel savings would likely not counterbalance the huge number of analysts needed for Gorgon Stare.

Despite the Gorgon Stare's potential usefulness, its use would unfortunately exacerbate the current information crisis that UAVs are already creating for analysts, consequently creating a human capital crisis for the U.S. Air Force that is already short on manpower. In addition to the projected analyst shortfall, the U.S. Air Force has not had enough trained remote pilots to execute all requested missions over the past few years. At various times throughout the past decade, several competing strategies have been considered or adopted to mitigate this personnel shortfall.

To meet the increasing number of UAV sortie requests, the U.S. Air Force has increased the number of remote pilots available to support UAV missions. To meet long-term projected demands, the Air Force will need to expand its UAV pilot training program. By 2009, the U.S. Air Force was training 200 two-man Predator and Reaper UAV crews, outnumbering pilots trained that year for all other U.S. fighter planes *combined.* This trend has continued throughout

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[398] *Ibid.*
[399] Bumiller and Shanker, *op. cit.*

2011.[400, 401] To achieve such impressive numbers, the U.S. Air Force has recently relaxed its requirement that UAV pilots be seasoned aviators from manned aircraft.[402] Today, new UAV pilots are only required to spend a few tens of hours in a (manned) cockpit – roughly the equivalent of a private pilot's license – to operate a UAV.[403]

Unfortunately, the U.S Air Force UAV training program has not been able to keep up with the growing demand for UAV pilots. In January 2008, the demand for UAV pilots was so serious that the Pentagon considered a proposal that would have suspended all Predator pilot training programs and immediately reassigned trainers and their aircraft to operational duty.[404] Dubbed "all in," the proposal was ultimately scaled back, in part because of some officers' fears that the plan resembled similar steps that had been taken by the German Luftwaffe during World War II to quickly get more planes in the air at the expense of German airpower's long-term effectiveness.[405]

Ultimately, the U.S. Air Force decided to take three steps that could be immediately implemented to meet UAV crew shortages. First, the tours of Predator crews were initially extended to retain trained pilots for longer periods.[406] Second, former UAV pilots were recalled from their subsequent posts.[407] Lastly, these Predator and Reaper crews were frozen in their positions indefinitely.[408] For UAV pilots who had already been working 13 hours a day, sometimes 6 days

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[400] Shachtman, *op. cit.*
[401] Austen, *op. cit.*
[402] Schneider, *op. cit.*
[403] *Ibid.*
[404] Shachtman, *op. cit.*
[405] *Ibid.*
[406] *Ibid.*
[407] *Ibid.*
[408] *Ibid.*

a week, the prospect of such grueling, open-ended service is likely psychologically challenging, a prospect which threatens the recruiting and retention of UAV pilots and future UAV programs.

To supplement these strategies, the U.S. Air Force has been investing in force-multiplying technological solutions that would enhance a UAV pilot's ability to control multiple UAVs simultaneously.[409] During an interview with Peter Singer, one official stated that having "a dedicated operator for each robot will not pass the common sense test."[410] To achieve this goal, the new Multi-Aircraft Control system allows UAV pilots to control up to four aircraft at once.[411]

However, research exists suggesting that such human multiplexing is problematic. In flight tests featuring UAV pilots operating multiple UAVs, the pilots tended to fixate all attention on one UAV at the expense of the others.[412] Additionally, a NATO study revealed that a UAV pilot's operational performance was reduced by half when controlling two UAVs compared to only one.[413] A report published on a remote operator's ability to control multiple ground robots at a time found a similar result.[414] According to Mark Draper, the technical adviser for supervisory-control interfaces at Wright-Patterson Air Force Base, a single UAV pilot could successfully manage up to a dozen UAVs if only fixed ground targets were under observation.[415]

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[409] Singer, *op. cit.*
[410] *Ibid.*
[411] Warwick, 2010
[412] Austen, *op. cit.*
[413] *Ibid.*
[414] Finkelstein and Albus, 2004
[415] Austen, *op. cit.*

Attempts are currently underway to improve UAV pilot performance while managing multiple aircraft. For example, much effort is being exerted to design remote cockpits that reduce the elevated mental workload needed to multitask. At Wright-Patterson Air Force Base, a new interface called the Vigilant Spirit Control Station was recently demonstrated, featuring a unique color-coded scheme that allows the pilot to quickly extract the most important flight and mission data.[416] Research has also been devoted into a sensor net that can be placed on a UAV pilot's head to monitor the brain's electrical activity during flight.[417] Such a device could be used in conjunction with heart rate and eye-movement monitoring to determine the pilot's attentive and emotional states.[418] If the pilot loses focus, attention could be restored by providing electrical stimulation to the brain's frontal lobe.[419] Alternatively, UAV control could be transferred to another pilot. To fight the perpetual boredom associated with most UAV flights, drugs could be developed to make the human pilots calmer and more attentive.[420]

Alternatively, research is being conducted to develop artificial intelligence that will handle the routine tasks associated with piloting UAVs. Mark Draper of Wright-Patterson Air Force Base suggested that UAV pilots could manage multiple UAVs if the machines could quickly transfer control to a human operator after autonomously recognizing a meaningful "anomaly" in the monitored environment.[421] If the job of piloting UAVs is so tedious and boring that pharmaceuticals and neural stimulation are ultimately needed to perform well, increasing degrees of UAV autonomy seem quite appealing as an alternate solution. Supporting the case for autonomy, U.S. Air Force engineer Bob Smith noted that "we thought the hard part would be making a vehicle do something on its own. The hard part is making it do that thing well with a

[416] *Ibid.*
[417] *Ibid.*
[418] *Ibid.*
[419] *Ibid.*
[420] Dahm, *op. cit.*
[421] Austen, *op. cit.*

human involved."[422] UAV autonomy would not eliminate the human's role as a machine performance monitor, a role more suitable given that a multitasking pilot has already been shown to be unable to effectively control multiple UAVs.

To create autonomous UAVs, the Pentagon is currently investing in "smart" sensors that can monitor the environment and alert humans when a significant anomaly has been detected.[423] Currently, the most fascinating and promising "intelligent" sensor is BAE System's Autonomous Real-Time Ground Ubiquitous Surveillance-Imaging System (ARGUS-IS) drone-mounted camera, which has been under development since 2007.[424] The camera has a 1.8 gigapixel resolution and is comprised of four arrays containing 92 five-megapixel imagers, which are the equivalent to cellphone camera chips.[425, 426] Similar to the Gorgon Stare, an onboard digital processor dynamically combines the images into a panoramic mosaic of the surrounding landscape.[427] When mounted on a Hummingbird helicopter UAV that can loiter over 15,000ft for 20 hours at a time, the ARGUS-IS can image 15 square-miles.[428] BAE Systems indicates that the sensor will ultimately be capable of imaging over 100 square-miles at a time, and will have a ground sampling distance of 15 centimeters.[429] In other words, each pixel will represent 6 inches of actual terrain. Such a system will be dynamically capturing so much data that not all of it can be transmitted back to ground stations in real time.[430, 431] Thus, a maximum of 65 cameras can be

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[422] *Ibid.*
[423] *Ibid.*
[424] "BAE SYSTEMS AWARDED $18 MILLION DARPA CONTRACT TO LEAD IMAGING SYSTEM PROGRAM," (See http://www.baesystems.co.uk/Newsroom/NewsReleases/autoGen_107105142443.html)
[425] Hambling, 2009
[426] Warwick, 2010
[427] *Ibid.*
[428] Hambling, *op. cit.*
[429] *Ibid.*
[430] *Ibid.*
[431] Warwick, *op. cit.*

independently monitored and zoomed in or out at any given moment.[432] The resolution is so good that individuals can be tracked.[433]

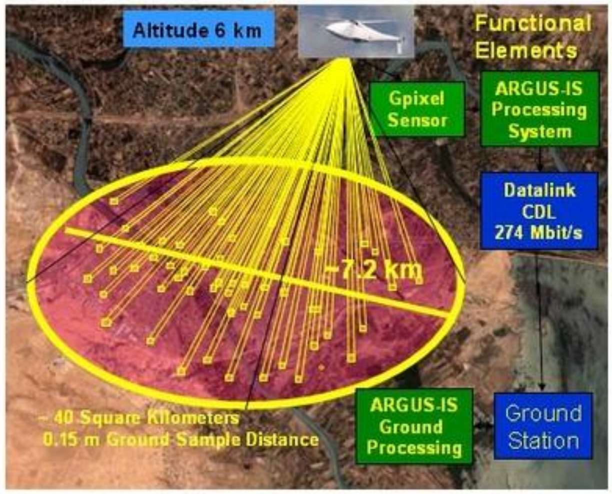

Figure 19: ***ARGUS-IS' Imaging Radius:*** *This image conceptualizes how the ARGUS-IS captures a panoramic image. Source: http://www.wired.com/dangerroom/2009/02/gigapixel-flyin/*

The most fascinating aspect of the ARGUS-IS is the artificial intelligence that is being implemented into the sensor's digital processor. Each of the individually streamed videos can automatically track interesting objects, such as a moving vehicle.[434] Additionally, the sensors can automatically detect and label any object that moves *anywhere* within the monitored landscape.[435, 436] To locate objects, each individual camera intelligently cooperates with the other cameras to determine where to search for motion. If one camera recognizes that its assigned area is unlikely to contain any interesting motion, the camera automatically reassigns itself to help another camera that has located a more complicated visual area or an area in which high-interest

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432 Hambling, *op. cit.*
433 *Ibid.*
434 *Ibid.*
435 *Ibid.*
436 Warwick, *op. cit.*

activity in more likely to be found.[437, 438] Tests of this Particle Swarm Optimization technique allowed an object of interest to be found 70 times faster than standard linear-scanning techniques.[439] Because such an advanced search routine allows tremendous resolution of interesting objects by devoting processing resources away from areas that are ultimately uninteresting to analysts, the number of false positive signals is also reduced.[440]

Thus, ARGUS-IS is a revolutionary smart-sensor that represents a combination of the Predator UAV's high-magnification camera and the Gorgon Stare's small-resolution wide-area cameras integrated into one dynamic acuity sensor. Not only does the ARGUS-IS locate its own moving targets unassisted by ground assets, but it can autonomously harness its vast magnification potential to provide a detailed picture of the target while tracking it. Such a design represents a striking improvement upon and departure from the human eyeball, as all visual resources can be devoted to the search process before creating a dynamic fovea within the visual field to better identify interesting targets as they are acquired. After an interesting target has been acquired for tracking, the camera's frame rate can be dynamically increased to such a great extent that individual bullets can be autonomously monitored as they fly through the air, thus allowing the sensor to trace the shot back to the shooter.[441]

When such sensors are operationally deployed, their tactical impact should be significant. Although likely best-suited for rural and wilderness environments not featuring many moving human targets, UAVs equipped with the Gorgon Stare or the Argus-IS will finally be capable of

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[437] Hambling, *op. cit.*
[438] Hambling, 2009
[439] *Ibid.*
[440] *Ibid.*
[441] Hambling, *op. cit.*

fulfilling the tactical reconnaissance role so desperately needed by the U.S. Air Force in the War on Terror. Future fully autonomous UAVs equipped with these sensors will not be restricted by the limited bandwidth that prevents constant transmission of all ARGUS-IS sensor data to a remote pilot because the UAV will be able to both process and act on all of the data at the local level, while occasionally sending small amounts of highly processed data to other users as needed. Such local processing also decreases at least two of the technical vulnerabilities outlined earlier in this paper; fewer transmissions significantly decrease the opportunities which enemy combatants can detect the presence of UAVs by monitoring the airwaves for video feeds and reduce the likelihood that the actual video feeds could be intercepted and monitored with cheap software, such as SkyGrabber. Additionally, the lack of continuous involvement from pilots and analysts would allow such tactical reconnaissance assets to be used around the clock without placing strain on military personnel.

In addition to tactical advantages, fully autonomous UAVs provide economic incentives compared to their remotely piloted counterparts by reducing reliance on the U.S. Air Force's most costly asset – its personnel.[442] For instance, an estimated $135,000 could be saved per pilot by down-sizing UAV pilot training programs.[443] Additionally, cost savings will occur due to reducing the number of salaried UAV pilots and analysts. Excluding development costs, the Global Hawk UAV's support costs are $88 million more expensive than the actual UAV, meaning that considerable cost savings can be achieved by removing expensive human elements from the equation.[444] Each in-theater solider that could be removed from the battlefield through the use of autonomous UAVs would yield large personnel savings, as each soldier stationed in

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[442] Austen, *op. cit.*
[443] Hoffman, 2009
[444] Singer, *op. cit.*

Afghanistan costs the military $850,000-$1.4 million per year.[445] The use of autonomous UAVs as low-orbit pseudo satellites combined with a significantly decreased need for real-time transmission capabilities could potentially reduce the need to launch new satellites, potentially saving billions of dollars.[446] Lastly, decreased transmission requirements would reduce the bandwidth of commercial satellite access that must be purchased each year to facilitate UAV operations.[447] At the commercial rate of $40,000 per MHz per year, automating a fleet of 50 Predator and Reaper UAVs could save up to $25 million per year.[448]

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[445] Shaughnessy, 2012
[446] Best, 2005
[447] Donley and Schwartz, *op. cit.*
[448] *Ibid.*

2.3.2.2 Development of Networked, Cooperative Micro UAVs

Although advanced sensor technology for larger UAVs, such as the ARGUS-IS, will allow these aircraft to locate potentially interesting exterior targets, such as militants or weapons, even a camera resolution of six inches is unlikely to accurately capture a person's unique facial features, specific behaviors, and equipment. Additionally, UAVs equipped with such sensors would be unable to visually monitor suspected militants located in interior settings, thus limiting their usefulness in urban environments. Indeed, even if such aircraft could accurately identify militants, their destructive Hellfire missile payloads would likely produce much collateral damage if used in cities, thus rendering current UAV lethal strike capabilities unsuitable. The capability to locate and strike targets within urban environments is becoming increasingly important has UAV strikes in Pakistan's remote countryside drive al Qaeda leadership into cities for protection.[449]

To address these deficiencies, smaller "micro" UAVs will be needed to complement larger UAVs equipped with wide-area sensors. Development of such UAVs is ongoing, with many successful breakthroughs occurring over the last two decades. Early technological limitations were overcome with the development of miniaturized micro electromechanical systems, such as gyroscopes, accelerometers, airspeed sensors, compact GPS receivers, and lithium ion-powered batteries.[450]

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[449] Bergen and Tiedemann, *op. cit.*
[450] Schneider, *op. cit.*

Such advances allowed the creation of the small Raven UAV, which could be hand-launched. Having less weight, more capable autopilot capabilities, and three-times the operational endurance of its predecessor, the Raven represented a significant achievement for providing very limited tactical reconnaissance capabilities directly to soldiers on the battlefield.[451] However, since it is launched by soldiers on the battlefield and has a relatively short range, the Raven's use is strictly limited to areas in which the U.S. military already has manpower, thus making it unsuitable for use in areas in which access is denied to U.S. soldiers. Additionally, the Raven is too large and flies too high to provide detailed urban and indoor intelligence.

Similar to artificial intelligence development and aspects of advanced sensor development, research efforts for creating the next generation of micro UAVs are turning to biology for inspiration. Specifically, researchers are in the process of creating micro UAVs that resemble birds and insects, both in appearance and flight mechanics.[452] The goal of such a design is to produce UAVs that blend in with the natural environment and penetrate air defense systems, thus attracting little attention while they collect detailed intelligence.[453, 454] Although the ability to remain discreet has tactical benefits by preventing militants from knowing that they are being observed, it provides the secondary benefit of reducing the local population's exposure to these surveillance tactics. Thus, the general population's support will not be eroded through the use of micro UAVs, especially when these UAVs are deployed in urban areas. Gathering intelligence without alienating local populations will allow the U.S. Air Force to become more relevant in COIN and UW campaigns.

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[451] *Ibid.*
[452] Bumiller and Shanker, *op. cit.*
[453] Clapper et al, *op. cit.*
[454] Dahm, *op. cit.*

The physical designs for these biologically-inspired micro UAVs are currently in development, and the initial technology demonstrations occurred in 2008.[455] A hummingbird UAV was demonstrated by AeroVironment – the maker of the Raven – in 2011 and was funded by DARPA, thus clearly indicating the military's interest in micro UAVs.[456] The hummingbird can reportedly fly 11 miles per hour and perch on windowsills, allowing it to gather limited intelligence inside buildings.[457] To create these artificial birds, flapping wing technology is being pioneered to recreate the physics of natural flight for both bird and insect UAVs.[458] Working wings allow these micro UAVs to hover in place while surveying a target, thus allowing the drone to operate in small spaces. Additionally, prototype claws and feet have been developed to allow these micro UAVs to stably land on a variety of objects, such as tree branches or power lines.[459] Because the dynamic coordination and control of artificial muscles involved in seamless high-speed landing is a complex process, autonomous landing capabilities will be required to control the micro UAV's muscles.[460] By 2015, the U.S. Air Force anticipates fielding semi-autonomous bird-like micro UAVs for a week at a time to detect harmful chemicals and explosives.[461]

Due to their less complex muscles, insect micro UAVs feature wing motion technology that is even simpler to design than artificial bird wings.[462] Current research efforts are focused on moth and fly micro UAVs that are equipped with sensors that can detect enemy personnel and nuclear weapons.[463] Ultimately, the Pentagon intends to field insect micro UAVs that weigh less than 10

[455] *Ibid.*
[456] Bumiller and Shanker, *op. cit.*
[457] *Ibid.*
[458] *Ibid.*
[459] Jean, 2011
[460] *Ibid.*
[461] Jean, *op. cit.*
[462] Bumiller and Shanker, *op. cit.*
[463] *Ibid.*

grams and with wingspans smaller than 2 inches.[464] Artificial insects could more easily and discreetly penetrate indoor environments than bird micro UAVs.

Within the next two decades, the military envisions that micro UAVs will possess advanced technologies that support discreet ISR missions. For example, micro UAVs will become increasingly autonomous by engaging in intelligence collection capabilities without receiving inputs from a remote human operator.[465] These micro UAVs will plan their behaviors in a manner that balances the need to remain covert with mission priorities, such as selecting the flight path to a target that best maximizes the drone's concealment.[466] The use of quiet electric motors will further decrease the probability that these drones will be detected.[467] Ideally, micro UAVs will achieve long operational endurance times by converting local biomass into energy and by recharging their electrical power supply by exploiting local infrastructures.[468]

In addition to ISR capabilities, micro UAVs are well-suited for performing precision targeted, lethal strikes. The U.S. Air Force undertook a 2008 research project – appropriately dubbed Project Anubis – to create a micro UAV with lethal strike capabilities.[469] At slightly over half a million dollars, the original plan called for micro UAVs equipped with sensors, data links, and a munitions payload "to engage time-sensitive fleeting targets in complex environments."[470] The FY 2010 DoD Budget briefly notes that Project Anubis was successfully completed, with a total

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[464] Clapper et al, *op. cit.*
[465] *Ibid.*
[466] *Ibid.*
[467] Hambling, 2010
[468] Clapper et al, *op. cit.*
[469] Hambling, *op. cit.*
[470] United States Air Force Committee Staff Procurement Backup Book FY 2008 Global War on Terror Budget Amendment, 2007

of $1.75 million being devoted to the project.[471] Such micro UAVs could deliver a precision strike with a poison needle, significantly reducing the likelihood that collateral damage would occur.

Considering that missile ordnance for larger UAV aircraft will soon weigh less than 5lbs and will be capable of autonomously tracking targets with an electro-optical seeker, it's not inconceivable that such lethal micro UAVs could actually double as ordinance for larger UAVs.[472] In theory, micro UAVs would be dispatched to a location designated by a larger UAV equipped with a wide-area sensor or by dismounted soldiers to collect additional data discreetly. Swarms of micro UAVs could potentially canvass a large area in tandem to search for potential militants and weapons, thus increasing the overall search efficiency in a manner similar to the Particle Swarm Optimization technique used by the ARGUS-IS's individual cameras to quickly extract mission essential information from a large amount of data. The technology supporting this cooperative search strategy has already been demonstrated in field experiments featuring 6 robots autonomously coordinating with each other.[473] Additionally, algorithms designed for autonomous multi-vehicle control have been demonstrated to effectively guide the coordination of 200 vehicles during simulation testing.[474] The development of interoperable software will ultimately allow large numbers of diverse UAVs to communicate with each other in future tests.[475]

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[471] Department of Defense Fiscal Year (FY) 2010 Budget Estimates, May 2009
[472] Hambling, 2008
[473] Clapper et al, *op. cit.*
[474] *Ibid.*
[475] *Ibid.*

To increase the effectiveness of autonomously cooperating robots searching a target location, sensor capabilities will become increasingly fractionated, thus enabling the physical diffusion of various capabilities among a decentralized network of multiple micro UAVs.[476] Through the widespread use of autonomous cooperative algorithms and data sharing, individual micro UAVs would not be required to possess all the capabilities needed to execute a mission, thus allowing micro UAVs to become highly specialized to perform certain tasks.[477] For example, different micro UAVs would be capable of performing lethal strikes, electro-optical imaging, electronic warfare, communication relay, and other advanced sensors, thus allowing these capabilities to be fielded at a relatively low cost through fractionated systems.[478] The exact combination of micro UAVs and network capabilities would be dictated by the given mission requirements.[479]

Using this autonomous distributed network, all data acquired by micro UAVs within the network would be shared with all other micro UAVs within the target area, thus extending the effective range of all UAVs throughout the network. This network "intelligence" will increase the survivability of *capabilities* due to redundant capability-elements spread throughout an autonomous network that can reconfigure the position of physical assets to compensate for any individual micro UAV losses.[480] Short-range communication technologies, such as burst mode transmission, radio frequency agility, and laser links will significantly decrease the probability that the individual micro UAVs can be detected, tracked, and electronically countered.[481, 482]

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[476] Dahm, 2010
[477] *Ibid.*
[478] *Ibid.*
[479] *Ibid.*
[480] *Ibid.*
[481] *Ibid.*
[482] Clapper et al, *op. cit.* (FY2009-2034 Unmanned Systems Integrated Road Map)

2.4 **Discussion**

Based on the major themes just explored – the foundational architecture and utility of UAV autonomy, advanced sensor development, and networked micro UAV usage – conclusions can be derived regarding the future interaction of these themes in increasing the U.S. Air Force's ability to strike militant targets while decreasing collateral damage to civilians and infrastructure, thus allowing the U.S. Air Force to become more effective in UW and COIN contingencies. The following diagram provides an overview of the elements and interactions that will govern the evolution of autonomous UAVs:

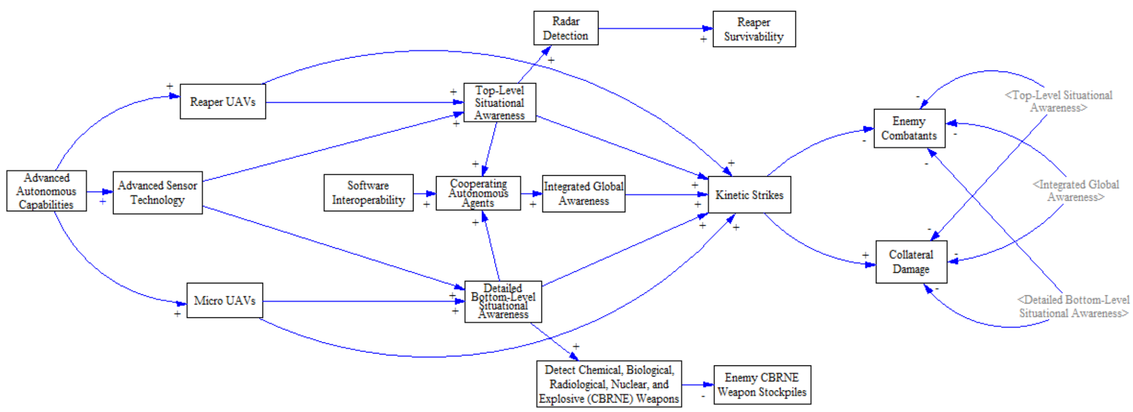

Figure 20: ***Overview of Autonomous UAV Strategic Vision***

The single most important technological advancement for future UAV usage is the development of *advanced autonomous capabilities* (featured on the left-hand side of the diagram) because these capabilities will be useful for all additional UAV models and supporting technologies, from intelligent sensors to intelligent munitions. Artificial intelligence research supporting UAV autonomy will increasingly focus on developing artificial neural networks that emulate human cognitive processing capabilities, with these capabilities likely occurring faster than expected due to technology's exponential growth.

Overall, automating UAVs for ISR and lethal strike functions will help manage the information overload crisis associated with UAV sensor data volume, reduce the demand for critical bandwidth because of significantly reduced wireless transmission loads, reduce the military's manpower strain in jobs supporting UAV missions, allow the U.S. Air Force to gather data around-the-clock, field more UAVs at once, and significantly decrease UAV vulnerability to electronic attack.

Two different categories of UAVs will use these advanced autonomous capabilities, with the first being the larger *Reaper UAVs*. Equipped with wide-area scanners like the 1.8 gigapixal ARGUS-IS, these Reaper UAVs can someday locate and track individuals anywhere within a 100-mile area with minimal help from ground sources, thus providing tactical reconnaissance capabilities to the U.S. Air Force ("*Top Level Situational Awareness*"). Their ability to detect radar (*Radar Detection*) will provide increased survivability in anti-access regions.

The second category of UAVs that will use advanced autonomous capabilities is *micro UAVs*. Equipped with miniaturized, fractionated sensors and disguised as small organisms, networks of micro UAVs can penetrate anti-access regions and blend into the environment. They can then work in tandem to quickly gather additional data in a discreet manner that supplements data acquired from larger UAVs many thousands of feet above the target (*Detailed Bottom-Level Situational Awareness*), especially in urban and indoor areas, thus allowing the U.S. Air Force to gather intelligence that is often lost when targets are destroyed by missiles fired by large UAVs from far above. These micro UAVs will be able to perform facial and voice analysis to identify known militant targets and could recognize specific weapons and behavioral patterns indicating potential terrorist involvement. When militants have been confidently identified, micro UAVs could strike using miniature ordinance, small arms, or other asymmetric means. Additionally, micro UAVs could *detect chemical, biological, radiological, nuclear, and explosive* material and subsequently neutralize the stockpiles.

As Reaper UAVs and micro UAVs are increasingly fielded in operational settings, the number of *kinetic strikes* against militant targets will also increase due to the increase in opportunities provided by additional targeting data. While this reality will increase the number of militants killed (*Enemy Combatants* Neutralized), an increase in kinetic strikes will also increase the total number accidental civilian deaths (*Collateral* Damage). However, as top and bottom level situational awareness is improved, the number of militants killed per strike will increase and collateral damage will be better avoided. This effect will be additionally magnified to the extent that all autonomous UAV sensor data can be shared with all other UAVs in the network, thus empowering individual UAVs with a greater basis for making decisions and choosing targets (*Integrated Global Awareness*).

Autonomous UAVs will allow the U.S. Air Force to productively participate in UW and COIN campaigns by serving as discreet tactical reconnaissance hunters that can quickly locate militant targets and execute necessary surveillance and strike actions in all environments and in a manner that does not undermine the war for the hearts and minds of the local populace. Most importantly, autonomous UAVs will perform these functions while reducing U.S. personnel exposure to dangerous settings.

Additionally, policymakers must realize that UAV usage also creates many societal challenges that must be addressed in tandem with increasing UAV usage and development. The relationship of future UAVs to the challenges illuminated earlier is summarized in the diagram below:

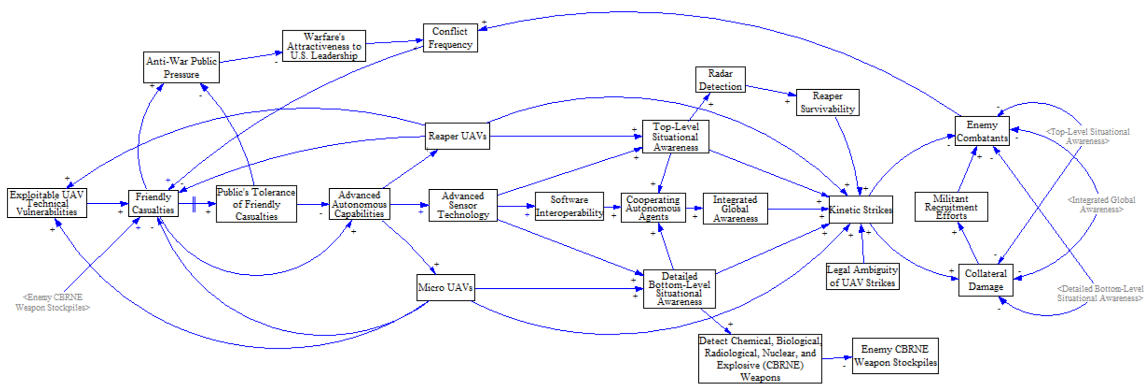

Figure 21: ***Overview of Autonomous UAV Advantages and Challenges***

Policymakers must be acutely aware of the possibility that UAV usage may be perceived as being so attractive that military action will be more quickly pursued than in the past to settle international disputes. In instances clearly resembling "just wars," the easier use of military power may prove advantageous for the greater good. Otherwise, to prevent unnecessary bloodshed, policymakers should consider potential options for increasing the public's "stake" in military campaigns to counter any general public disinterest in warfare that results from heavy reliance on "costless" UAVs.

The international community should also monitor and discuss the ethical issues associated with UAV usage to determine agreed-upon limitations as it has with other weapons, such as landmines. The earlier these guidelines can be the determined, the more easily they can be implemented into the UAV development process while it is still in relative infancy. Additionally, legal accountability should be clearly established for instances in which autonomous UAVs make mistakes.

Lastly, policymakers and military planners alike must be prepared for the possibility that UAVs could be technologically vulnerable. For example, malware, back doors, and viruses could be introduced to UAV hardware from anywhere in the world and at any time, thus compromising their ability to execute their missions. If exploited, such vulnerabilities could immediately render the entire UAV fleet useless, if not an outright liability. Additionally, technological overconfidence may compel policymakers to mistakenly believe that the technology is sufficiently advanced to handle missions before it is actually ready. In both cases, the U.S. would suddenly find itself in a war that it is ill-equipped to fight. To reduce the risk associated with both possibilities, much effort should be invested in developing verification programs that reliably and robustly demonstrate UAV technological capabilities when exposed to an array of scenarios.

Although it is currently unclear how the overarching dynamics among the various UAV advantages and challenges will play out over the next few decades, artificial intelligence design, UAV development, and UAV employment are rapidly increasing and are here to stay. Unlike the arrival of many previous technologies that revolutionized warfare, autonomous UAVs will fundamentally change how nations wage war by removing humans from traditional warzones and further eroding humanity's historical role in warfare. Consequently, their use will provide the U.S. with a much-needed asset for countering violent insurgencies and frustrating militant attempts to break the U.S.'s will to fight by killing U.S. soldiers. Given the continuing prevalence of irregular warfare and having been at war with al Qaeda and the Taliban in Afghanistan for over a decade, the advantages of developing autonomous UAVs are clear.

Although the development of autonomous UAVs seems plausible within the next few decades and will likely provide the U.S. with numerous tactical military advantages, some may argue that the real question is whether the U.S. *should* empower autonomous robots to perform lethal strikes. Such a concern is motivated by questions about whether a robot would truly appreciate the ethical nuances needed to appropriately weigh life-and-death decisions that are intricately connected to war, with the fear being that these autonomous UAVs would too frequently perform lethal strikes, thus causing unnecessary collateral damage. Although it is too early in the development process to define the extent to which autonomous UAVs could mimic ethical reasoning, autonomous lethal strike capabilities could be considered acceptable if they do not produce more collateral damage than alternative manned-aircraft strikes used to achieve the same effect. Such a comparison recasts the ethical question into an empirical one, which can be definitively answered as UAV development progresses.

Tactical advantages aside, another equally compelling reason for pursuing autonomous lethal technologies is the fact that at least 40 countries are currently developing their own UAV programs. As Peter Singer of the Brookings Institute has pointed out, continued international investment in UAV technology is here to stay, whether the U.S. chooses to abandon it over ethical concerns or not. If the U.S. chooses to be the leader in pioneering autonomous UAV technology, then the U.S. can greatly influence the technology's progression and maturity by ensuring that its UAVs operate in a manner that respects human rights and humanitarian concerns. Otherwise, the U.S. would allow other countries to dictate the degree to which ethical concerns are incorporated into UAV design. Given the human rights record of some of the countries with UAV programs, such as Iran and China, such ethical considerations are likely to be ignored. Indeed, any U.S. abandonment of UAV research would additionally increase foreign UAV appeal by virtue of the fact that such technology would immediately give other countries an asymmetric tactical advantage over the U.S., further eroding any international interest in fielding ethical weapons.

To the quintessential heroic figure of General George Patton, the thought of robotic vehicles engaging in offensive operations would likely be an affront to all that was pure and honorable about warfare. Indeed, he once proclaimed that "many, who should know better, think that wars can be decided by soulless machines, rather than by the blood and anguish of brave men."[483] For better or worse, the arrival of autonomous UAVs will herald the beginning of the post-heroic age he disavowed. It may be that proper design and application of UAV technology will reduce the blood and anguish by limiting or even preventing future conflicts. By carefully examining the UAV's future capabilities with a keen eye to the specific, projected needs that they will fulfill, it is hoped that the present research will contribute to forging the strategic vision necessary to guide UAV autonomy design decisions and policy choices to ensure that the U.S. has the right tools needed to succeed in the new age of 21st century conflicts.

[483] http://www.generalpatton.com/quotes/index3.html

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