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Military Robotics and Collateral Damage

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Abstract

We explore a concept of a combined force of air and ground combat robots that could act in a force protection and close fire support roles for a human force. The combat robots would operate primarily in the revenge-fire mode, detecting hostile fire and returning fire in a largely autonomous fashion, rapidly and accurately. Such concepts raise important questions in terms of their impact on collateral damage. In a broader context, western warfare in general places a continuously growing emphasis on issues of collateral damage. Thus, developers of combat robots must seek means to minimize collateral damage, specifically non-combatant fatalities. Planning and control of effects produced by combat robotic force should be focused in equal measure on what is not destroyed as well as on what is destroyed. In this paper, we review emerging concepts of combat robots, propose a model for estimating the risk of non-combatant fatalities, and offer a step toward quantitative comparison of the ratio of non-combatant to combatant fatalities expected in human and robotic engagements. We argue that use of combat robots with the right rules of engagement can dramatically reduce the risk of collateral damage as compared to manned combat operations.

1 Introduction

A number of organizations are actively pursuing the development of armed air and ground combat robots that would operate with potentially significant degrees of autonomy. The emerging combat robotics technology combined with corresponding operational and command and control concepts hold promise for highly flexible and lethal effects against the hostile forces, but raise important questions in terms of their impact on collateral damage. Seen in a broader context, western warfare in general places a continuously growing emphasis on issues of collateral damage. Thus, developers of combat robotic platforms and their employment concepts must seek means to minimize collateral damage, specifically non-combatant fatalities. Command and control of effects produced by combat robotic force should be focused in equal measure on what is not destroyed as well as on what is destroyed.

Traditionally, one common measure of effectiveness of a command, control and targeting strategy is the resulting probability of kill (P_k) of targets. For the purposes of the studies reported in this paper, we have focused on the number of combatant fatalities C as a measure of combat effectiveness, where C is determined by both the combination of P_k and the number of munitions fired. However, in modern western warfare a number of important concerns dictate a great attention to the collateral damage. In particular, effects-based targeting explicitly acknowledges the importance of avoiding collateral damage and structuring engagements to limit destruction as part of their explicit objective. Consequently, for evaluating different command, control and targeting strategies for combat robots, metrics must capture both the destructive effectiveness of the strategy and the extent of collateral damage. Given such metrics, one could construct a predictive model that would evaluate a specific C2 and targeting strategy for combat robots.

Collateral damage can include property damage, destruction of the environment and societal infrastructure, and the wounding and death of civilians. In this paper, we have chosen to focus on one metric of collateral damage: the number of non-combatants fatalities resulting from an engagement, which we label NC. This metric is directly measurable and has the benefit of been recorded (sometimes) in historical data for human conflicts. Unlike property damage, human fatality is an unambiguous state with only two values, and it does not need to be indexed for inflation, adjusted for currency conversion rates, or modified for different styles of construction or social conventions. It is arguably by far the most important metric of collateral damage in a societal and political sense.

An effective C2 strategy for modern warfare will maximize the number of hostile forces killed, C, while minimizing the number of non-combatants killed, NC. We are particularly interested in evaluating robotic command and control schemes from the standpoint of their predicted NC/C ratio. An effective strategy will minimize this ratio. Two key issues are immediately apparent:

1. What are typical historical NC/C ratios for representative human conflicts?
2. How can one predict an NC/C ratio for a given set of combat robots operating under a particular command, control, and targeting strategy?
3. How would the NC/C ratio characteristic of a combat robotic force compare to that of a conventional manned force?

In this paper, we attempt to take a step toward answering these questions. We outline a scenario and an operational concept of a combat robotic force as a case study to illustrate a predictive model for NC/C for robotic combat and compare it to both modeled and historical NC/C ratios for human combat. More broadly, we seek to introduce a new area of inquiry in command and control research for combat robots: how to model, predict, and *minimize* the NC/C ratio. Specifically in this paper, we review emerging concepts of combat robots and their employment, review the historical NC/C ratios for human combat, propose a model for estimating the risk of collateral damage, and offer a quantitative comparison of collateral damage expected in human and robotic engagements. We argue that proper use of combat robots can dramatically reduce the risk of collateral damage compared to conventional practice and concepts of operation. In conclusion, we propose key research and technology challenges related to the reduction of non-combatant casualties through the use of intelligent robotic command and control strategies.

2 Combat Robots are Here

For the purposes of this article we define a combat robot as an autonomous unmanned platform capable of applying lethal or non-lethal effects to enemy assets. This definition excludes teleoperated platforms, or those that are limited to information collection. To qualify as a combat robot, the platform should be able to identify an enemy target (or at least find a location of a pre-identified target) and be able to apply effects to that target – all of this without a strict requirement to involve a human operator. Of course, such autonomous capability does not preclude either the possibility or desirability of having a remote human operator to confirm the target and to authorize weapon release, or to have a remote human to provide command-by-negation supervision, depending on the rules of engagement.

There are a number of active development programs (e.g., [14, 15, 16]) that are likely to produce highly advanced unmanned combat platforms with a significant degree of autonomy. Although these programs are yet to bring working systems to the battlefield, it can be argued that in fact combat robot have already participated in human warfare for hundreds of years. A sea mine or a land mine is a basic combat robot: it can identify an enemy ("if he bumps into me, he must be an enemy") and apply an effect. Homing torpedoes, heat-seeking missiles, GPS-guided bombs and artillery rounds, and cruise missiles are more recent examples of combat robots – having been released on a mission they navigate autonomously toward the enemy (via its signature or location specification), detect the proximity of the target, and apply force.

Similar to them in several fundamental aspects, the upcoming generations of combat robots will continue the conceptual lineage of these earlier autonomous weapons but at a qualitatively new level of sophistication. They will be able to maintain their presence in the battlespace with long endurance periods, to plan and execute a broad repertoire of actions (complex movements as well as perception and communication) in order to locate, approach and identify the enemy, and to apply a range of effects repeatedly to multiple targets.

Also similarly to existing autonomous weapons, the new generations of combat robots raise an important concern -- would they introduce a greater risk of fratricide and collateral damage?

3 Operational Use and Technical Feasibility of a Combat Robotic Force

To make the following discussion more concrete, consider the following hypothetic scenario involving employment of combat robotic forces. A blue force is executing a mission in an urban environment with significant presence of non-combatant population. The red force consists of irregular infantry armed with small arms, rocket-propelled grenades and man-portable surface-to-air missiles. Consistent with the demands of such an environment, conventional dismounted infantry constitutes the core of the blue force. However, their close fire support and force protection is provided by less familiar assets: a team consisting of robotic combat rotorcrafts and robotic combat ground vehicles.

As the blue infantry advances through the alleys and intersections of the city, the red force attacks them from fire positions at the windows and roof of the buildings while rapidly maneuvering through the familiar terrain and exploiting the difficulties of distinguishing irregular, non-uniformed combatants from non-combatant civilians. Historically, in such a combat there are significant risks of blue casualties and of unintended non-combatant fatalities caused by blue fires.

In this case, however, employment of robotic fire support brings important benefits as compared to conventional, human-operated fire platforms. First, the survivability of the blue human infantry can be significantly enhanced. Our simulation-based studies suggest that attrition of blue human force may be reduced due to at least two factors: (1) when the blue infantry faces enemy fire, the agile, highly-automated and autonomous C2 system of the robotic combatants can bring a supporting fire platform (e.g., an armed robotic rotorcraft) to the enemy much faster and closer (and with less concern for the platform's safety) than would be prudent and feasible for a conventional manned platform; (b) if and when a blue robotic platform is shot down, the blue infantry does not need to come to the rescue of the crew as would be necessary in the case of a manned platform. Further details related to the potential impact of robotic combatants on blue force survivability are outside the scope of this paper.

Second, and particularly remarkable, the non-combatant casualties can be also significantly reduced. Several factors are at work here. Robotic combatants can afford to come closer to the enemy fire sources than would be acceptable for a manned platform. The closer range allows more accurate fires and smaller weapons with less risk of affecting nearby non-combatants. Further, in our scenario the primary mode of operations of the robotic combatants is the revenge fire. Robotic combatants use a range of acoustic and visual signatures to identify and locate the sources of hostile fire more accurately and rapidly than a human would. This reduces the probability of an unintentional fire at a misidentified non-combatant or of a fire at a misidentified location of an enemy combatant. The remainder of this paper discusses these issues in detail.

One might wonder if such an ambitious vision of a combat robotic force is even remotely feasible in near term from the technical perspective. We believe that the answer is affirmative. Although a detailed discussion of technical approaches to building such robotic force is outside of the scope of this paper let us mention several key technical requirements and promising advances toward meeting them.

The last few years have seen steady progress toward credible capabilities in *autonomous mobility* in complex terrain, both air- and land-based. In particular, ladar-based near-real-time mapping of terrain offers an approach to cooperative mobility where an airborne robot generates a high-resolution three-dimensional terrain model that its ground-based buddy can then use for effective navigation (e.g., [17]). In this manner, the challenges of *obstacle detection and avoidance* are greatly simplified. *Perception of friendly forces,* critical for avoidance of fratricide, can be accomplished using approaches similar to those currently applied to blue force tracking (e.g., [18]). If revenge fire is accepted as a key mode of operation, then *enemy detection and targeting* can be accomplished partly by impressively accurate acoustic and video shooter detection techniques which saw rapid advances recently (e.g., [19, 20]). Given an accurate GPS location of the hostile fire source, a robot could employ a GPS-guided missile or use recently demonstrated GPS-based techniques for aiming its direct fire weapon or a laser designator. Finally, highly promising advances are made in the techniques for command and control of combat robots, e.g., [21]. Overall, it appears that all key technical enablers are soon to be available for combat robots to plan an effective tactical course of action, to maneuver rapidly and effectively in a complex, dense and dangerous environment, to know where the friendly forces are, to find enemy shooters, and to direct at them accurate fires.

Yet, we are still left with the question: would all this lead to an unacceptably high risk to non-combatants?

4 Analysis of Non-Combatant Fatalities

To understand implications of combat robotics in terms of its potential for combat effectiveness and collateral damage, we first review historical data regarding NC/C ratios in human armed conflicts. To predict robotic combatants' NC/C ratios, we develop an analytical model that relates collateral damage to weapons' effects radius, range to target, probability of detection, probability of false alarm, pointing accuracy, CEP of the weapon, CEP of the detection, and density of non-combatants. We compare the predictions of the analytical model to NC/C ratios in historical human conflicts and to the NC/C ratios estimated for robotic combat. We show quantitatively a potential for the reduction in collateral damage that could be achieved with robotic forces combined with innovative command and control technology.

4.1 Historical Data on Non-Combatant Fatalities in the 20th and 21st Centuries

To better understand how new concepts for combat robots could affect collateral damage, we have attempted to establish a typical range of war-caused non-combatant death, specifically the NC/C ratio, by surveying existing compilations of fatalities occurring as the result of wars or armed conflicts in the 20th and 21st centuries [1-13]. Our sources and several representative estimates of combatant and non-combatant deaths for 10 conflicts are tabulated in Table 4-1. These statistics comprise a sample of conflicts covering an historical time period from 1916 through 2003 and a range of intensities from small engagements occurring over a period of a few days in urban settings to global-scale warfare that occurs over a period of years in virtually all environments on land and sea. Numbers of fatalities cover a six order of magnitude span. Note that we have broken out Baghdad in 2003 as a separate conflict in addition to Iraq 2003 as a whole (including Baghdad fatalities) in order to include a purely urban/suburban set of engagements in the sample.

Conflict	**Dates**	**NC-Low**	**NC-Hi**	**NC-Mean**	**C-Low**	**C-Hi**	**C-Mean**	**Source**
WW1	1914-1919			**13,000,000**				13
							8,500,000	10
							7,734,300	6
	Overall Mean			13,000,000			8,117,150	
WWII	1939-1945						12,948,300	6
				13,000,000			20,000,000	13
				13,000,000			**15,164,300**	10
Korea	1950-1953			1,633,000			1,890,000	10
		400,000	3,000,000	1,700,000	582,000	2,000,000	1,291,000	8
	Overall Mean			**1,666,500**			**1,590,500**	
Vietnam	1960-1975	486,000	840,000	**1,330,000**	663,000	1,140,000	**1,235,000**	8
Iraq-Gulf War	1991		3,664	**3,500**	20,000	26,000	**23,000**	1
		2,500	3,000	2,750				5
Chechnya-Russia	1999-2002			**30,000**	17,817	22,117	**19,967**	7
Kosovo	1999	500						2
Afghanistan	Oct-Dec 2001	3,073	3,597	3,335				4
		1,000	1,300	1,150			**3,602**	2
				3,500				7
	Overall Mean			**2,662**				
Jenin and Nablis	Apr-02	64	76	**70**	73	105	**89**	11
Iraq-OIF	Mar-May2003	3,200	4,300	**3,750**	7,600	10,800	**9,200**	1
		5,951	7,590	6,771				12
Baghdad	Mar-May2003				1,700	2,120	1,910	1
		1,990	2,357	**2,174**	2,224	3,531	**2,878**	1

Table 4-1. Combatant and non-combatant fatalities data used to characterize the range of NC/C ratios. Bold numbers are used in subsequent plots. Caution: these numbers illustrate trends but not necessarily quantitative conclusions.

We will be first to emphasize that the historical data we were able to find, as well as the conclusions based on these data, must be viewed with a great deal of caution. The sources are of very uneven quality and authority. The data cited by the sources are often of uncertain origin and definitions. Methodological difficulties are numerous and profound.

We did attempt to select sources that appear to be careful in documenting their methodology and the origin of their data. We also tried to use the same source for multiple conflicts where the source provided data for multiple conflicts. Where there were several differing sources without any reason for preference, we took an arithmetic mean of their estimates. Still, this brief, preliminary review of data makes no claims of methodological rigor and leaves much for future researchers.

Some variance in data (Table 4-1) relates to the definition of war-caused fatalities. For example, in our survey we tried to exclude sources that included fatalities arising from secondary effects of war such as famine, the collapse of societal infrastructure, the enhanced spread of disease, or genocide. While these effects can kill more people than direct violence, we wanted to understand the trends for non-combatants killed as a direct result of military engagements. For example, Zbigniew Brzezinski refers to this methodological problem when he writes [13]: “Civilian casualties--as actual byproduct of hostilities (and not of deliberate genocide)--accounted for about 13,000,000 women, children, and older men during World War I and for about 20,000,000 during World War II…”

A second cause of disagreement among sources, a cause that has become increasingly prevalent in recent decades, is that opposing factions may define non-combatants differently. For example, reports of non-combatant deaths for engagements between Israeli forces and Palestinian irregulars differ depending on which side is reporting the fatalities. In one engagement in Jenin running from April 3rd to the 11th, 2002, both sides agreed that 52 Palestinians were killed, but Israeli government sources cite 14 non-combatants and 38 combatants, while Human Rights Watch cites 22 non-combatants and 30 combatants [11].

Such discrepancies can result from political biases of the source, but may also result from differences in definitions. With growing involvement of irregular forces in recent conflicts this discrepancy in definitions and the increased room for political bias has helped to widen the variance of estimates of non-combatant fatalities among sources. Because it has become increasingly important politically over time to limit the number of non-combatant deaths, there exists an increasing incentive for one or both sides to under count or over estimate casualties. For example, recent claims of non-combatant fatalities during the force-on-force phase of the 2003 Iraqi war vary by as much as a factor of two depending on the source (e.g., [1, 12]). It is perhaps not coincidental that the direction of divergence tends to be the direction that supports the reporting source's political agenda.

Of course a common cause of variability in fatality estimates is that non-combatant casualties are not always reported or tabulated in an accurate manner, and often not at all. While one would expect to see this effect less pronounced in more recent times, this is not always the case. For example, estimates of non-combatant deaths during the American-Vietnamese war show some of the greatest variance in our sample of conflicts, despite the fact that it was one of the most extensively covered wars in history and body counts were a standard feature of nightly news broadcast in the United States during that conflict.

Given the variability of fatality estimates, we have chosen to plot non-combatant fatalities as a function of combatant deaths to establish general trends. Figure 4-1 shows non-combatant deaths plotted against combatant fatalities on a log-log scale for the 10 conflicts listed in Table 4-1 (Baghdad 2003 listed separately from Iraq 2003 as a whole) spanning the time period from 1916 through 2003 and ranging in scale from a few dozen deaths to tens of millions.

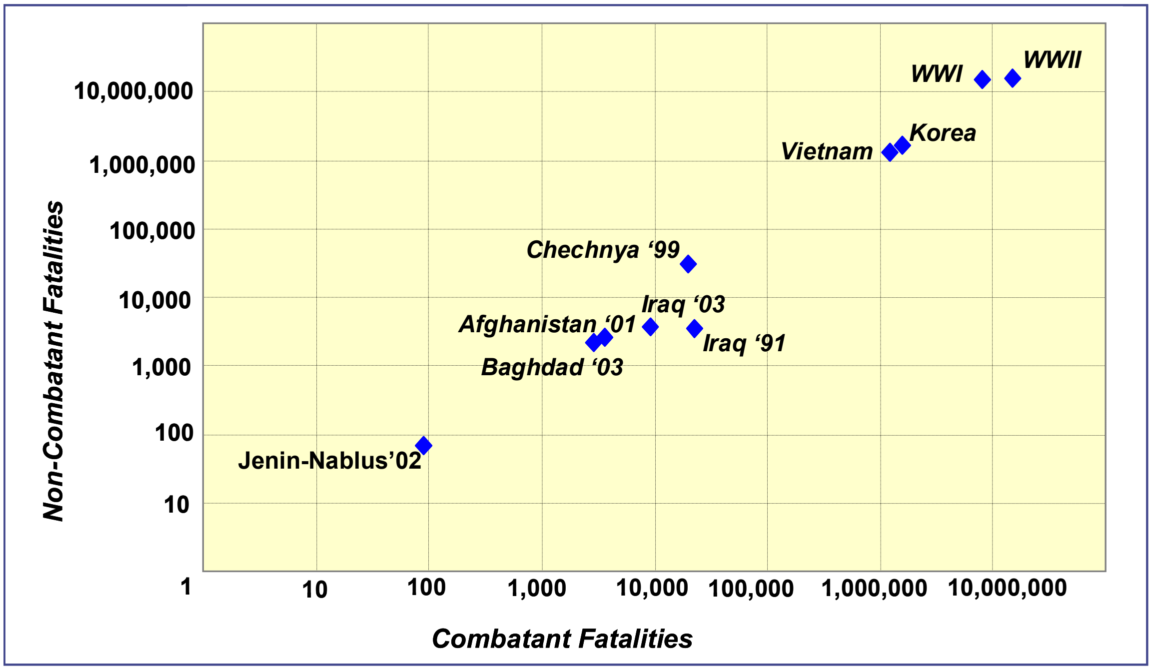

Figure 4-1 Non-combatant versus combatant fatalities for several conflicts since WWI compiled from Table 4-1.

Nevertheless, what can be seen from Figure 4.1 is that despite conflicts spanning nine decades and six orders of magnitude in casualties, most data cluster along a trend line of one non-combatant fatality for every combatant fatality. To attempt to provide an upper and lower bound on the non-combatant to combatant fatality ratio (NC/C), we plotted two trend lines on top of Figure 4.1 to show the NC/C ratio of 0.5 and 2.0. These trend lines are illustrated in Figure 4.2. It is apparent from Figure 4.2 that most of these conflicts fall between the ratios of one non-combatant for every two combatants and two non-combatants for every combatant fatality.

While the statistics from the Project for Defense Alternatives [1] place the Iraq war of 2003 just below the 0.5 NC/C trend line, taking other estimates of non-combatant deaths (for example, [12]) yields a ratio closer to 1.0. The only extreme outlier to the 0.5 to 2.0 NC/C ratio rule in our sample is the Iraqi Gulf War of 1991 where combatant casualties far outstripped those of non-combatants. The NC/C ratio for Iraq in 2003 compared to Iraq in 1991 is particularly noteworthy in that the 2003 engagement used 67% precision guided munitions compared to only 6.5% in the Gulf War of 1991 [1] making the Gulf War appear to be even more of an anomaly. We have not made a detailed analysis of the abnormally low Gulf War NC/C ratio, but speculate that part of the explanation lies in the nature of the engagements which were more classic force-on-force fire fights and with a much more prolonged air campaign against well know Iraqi position that took place in remote desert areas. Ground combat began after months of undisguised preparation that provided civilian populations ample time to flee the combat zone. In contrast, most of the fighting in the 2003 Iraq conflict occurred in and around urban areas and high density agricultural regions with only a short period of aerial bombardment as a prologue.

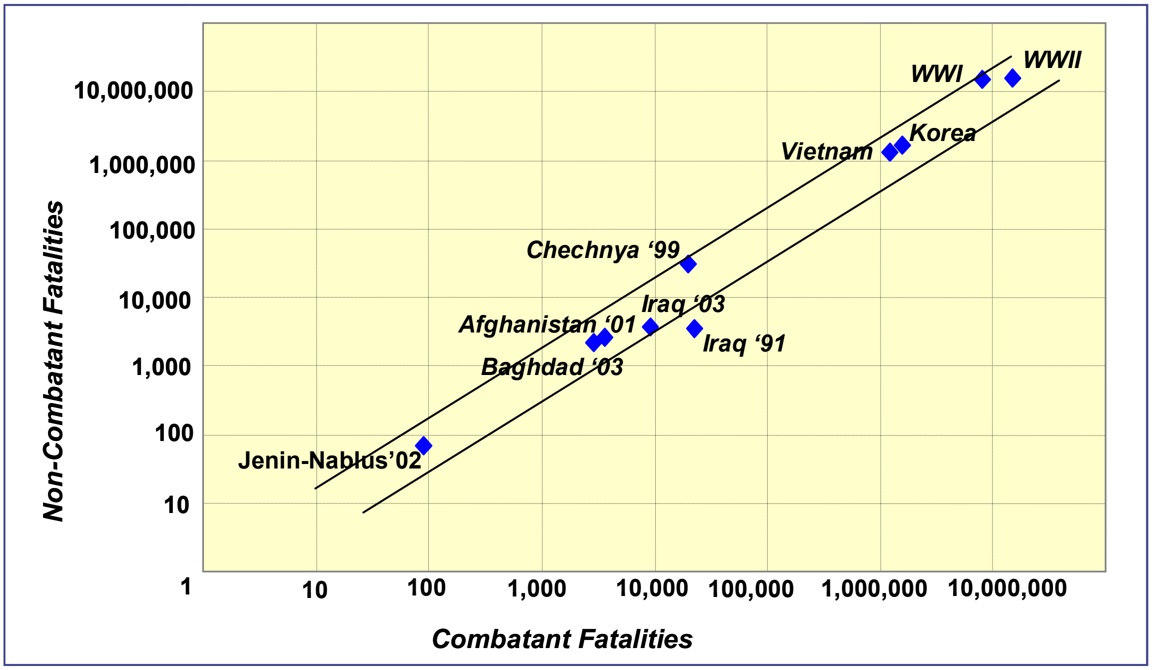

Figure 4-2. The ratio of non-combatant to combatant fatalities for many conflicts falls between 0.5 and 2.0 for the data from Table 4-1.

4.2 Causes of Non-Combatant Fatalities

Three principal causes of non-combatant fatalities and high NC/C ratios were considered:

> NC-1: Incidental deaths caused by non-combatants being present in the weapon's effects area when a weapon is released and its warhead exploded.
>
> NC-2: Inaccurate fire that does not kill the targeted combatants (thereby necessitating firing again), but that creates an additional possibility of death by cause NC-1.
>
> NC-3: Miss-directed fire that is incorrectly, but accurately, aimed at a non-combatant in the mistaken belief he is a hostile combatant. This results in both the need to fire again at the real combatant (as in case NC-2) and also has the effect of potentially directly causing a non-combatant death if the weapon accurately finds its target.

To a first order, the effects of factor NC-1 can be modeled as being directly proportional to the population density of the targeted area and the weapon's effects radius. Using weapons with the smallest effects area needed to destroy the target will minimize NC deaths caused by cause NC-1. To minimize the effects of contributions by factor NC-2, it is desirable to using larger ordinance with a wider weapon's effects area along with increasing the precision and accuracy of the fire. This strategy can raise the NC/C ratio by raising C fatalities, but it also can raise NC fatalities by exacerbating deaths caused by NC-1. Therefore, to lower both NC-1 and NC-2 causes of NC fatalities one should focus on increasing the precision and accuracy of fire. This objective can be accomplished by a C2 strategy that gets a robotic platform as close as possible to its target, or that reduces the target and weapon's platform location uncertainty, or that increases the pointing accuracy of the robot's weapon, or that uses a more accurate weapon (reducing its CEP), or any combination of these. Reducing factor NC-3 is a target detection problem that we do not address here, except to model it as a relationship between a probability of detection (P_d) and a probability of false alarm (P_{fa}) for whatever target sensing strategy is employed.

4.3 A Parametric Model of Collateral Damage

	Robotic	**Unmanned 1**	**Unmanned 2**
Range To Target (m)	106	300	300
Pd	0.8	0.3	0.3
Pfa	0.0016	0.006	0.006
Target Location Error (m)	1	3	3
Weapon	small rocket	medium missile	small rocket
Blast Radius (m)	3	6	3
CEP of weapon (m)	1	1	1
Density of NC (NC/Km^2)	175	175	175
Prob. Kill (P_k)	0.69	0.28	0.15
Prob. Collateral Dmg (P_{knc})	0.05	0.68	0.05
NC/C Ratio	0.07	2.45	0.34

Table 4-2. Key parameters used for robotic combatant's engagement and for two versions of a manned combatant's engagement. Simulated weapons models included a hypothetical medium-sized missile and a small 70mm class rocket. Our data is illustrative and may not represent the performance of any actual weapon

To assess the potential performance of combatants (conventional manned or robotic) in terms of collateral damage we developed a parametric model that relates the three causes of NC deaths to operational and technical parameters such as range to target, P_d, P_{fa}, weapon's effect radius, weapon's CEP, pointing accuracy of the robot with its weapon, etc. The full parametric model includes more than 40 parameters accounting for many aspects of the weapon, platform, command and control algorithm, target acquisition and other first-order effects.

As an initial case study, we choose to model an air to ground engagement where an air vehicle (manned or robotic) attacks dismounted hostile infantry targets on the ground using GPS guided munitions. We modeled hypothetical missiles and bombs across a range of accuracies and weapons' effects areas similar to munitions in order to approximate the range of weapons represented by bombs and missiles such as the small diameter bomb, a 70mm rocket, a small missile, etc. Because we used hypothetical weapon models, our data is illustrative of combat attrition and may not represent the performance of any actual weapon.

Our approach to parametrically modeling and predicting an NC/C ratio for such an engagement was to select a value of C, representing a particular size engagement, and then calculate the number of munitions required (N_w) to achieve C based on a parametrically modeled probability of kill per combatant fatality: $N_W = C/P_k$. NC can then be calculated as the probability of causing a non-combatant fatality per weapon's release, P_{knc}, times the number of munitions released to achieve a specific value of C: $NC = N_W * P_{knc} = C * P_{kn} / P_k$. A graph of NC = ϕ(C) can then be plotted and compared to historical data. The calculation used to determine P_k and P_{knc} are described next.

P_k is approximated here by calculating the probability of a kill if the weapon falls within the 50% probability circular error ellipse (CEP_{50}) about the target plus the probability of kill if the weapon falls outside the CEP_{50} area times the probability that the target would have been detected to begin with: $P_k = Pd*(0.5*P_{kcep}+0.45*P_{\overline{kcep}})$ where P_{kcep} is the probability of killing a target that is inside the weapon's CEP and $P_{\overline{kcep}})$ is the probability of killing a target that is outside the weapon's CEP. The values for killing a target in the CEP can be calculated as follows:

$$P_{kcep} = P_b \approx 1.0 \qquad \text{if } W_b \geq CEP_{50}$$

$$= P_b*(W_b/CEP_{50})^2 + (1-(W/CEP_{50})^2)*(1+P_s(CEP_{50}))/2 \qquad \text{if } W_b < CEP_{50}$$

where P_b is the probability of a dismounted human fatality in the blast radius of the weapon, and W_b is the blast radius of the weapon. The function $P_s(R)$ is the probability of kill as a function of range, R, from the weapon impact point. P_s is calculated using a linear approximation to the weapon's lethality profile for a simulated missile or bomb at ranges beyond the blast radius.

The probability of killing a target outside the CEP_{50} area can be approximated by:

$$P_{\overline{kcep}} = (P_s(CEP_{50}) + P_s(CEP_{95}))/2 \qquad \text{if } W_b < CEP_{95}$$

$$= P_b \approx 1.0 \qquad \text{if } W_b \geq CEP_{95}$$

where CEP_{95} refers to the circular error ellipse inside of which there is a 95% probability that the weapon will impact. CEP_{95} is calculated using a Gaussian fit to the CEP_{50} values.

A key part of the model is the computation of CEP_{50} – a value that depends on the flight accuracy of the weapon, the target location accuracy, the weapon's platform's pointing accuracy, and the weapon's platform's own location accuracy including both INS and GPS errors – all of which are modeled individually and combined to get a system CEP.

Once a probability of kill for a target is modeled, the probability of killing a non-combatant, P_{knc} can be calculated as the probability of mistakenly targeting a non-combatant (essentially the probability of a false alarm) plus the probability that a non-combatant will be in the weapon's effects splash zone by coincidence at the time of impact multiplied by the probability that the weapon's effects will kill the non-combatant:

$$P_{knc} = P_k * P_{fa} / P_d + P_b * W^2 * \pi * D + P_{ks} * W_{\max}{}^\wedge 2 * \pi * D$$

where W_{max} is the distance from weapon impact at which the probability of kill falls below a threshold value close to zero. D is the density of non-combatants in an area, and P_{ks} is a probability of kill beyond the blast area up to the maximum extent of weapon's effects area as approximated for a particular class of hypothetical weapons.

4.4 Collateral Damage Estimates for Robotic and Manned Combatants

The model outlined above was used to calculate non-combatant fatalities as a function of combatant fatalities for (a) an engagement executed by a robotic combatant and (b) an engagement executed by a conventional manned combatant. The model was set up to compute collateral damage for an air-to-ground strike using a small hypothetical GPS guided rocket for the robotic combatants. For the modeled human combatant, both a medium sized hypothetical missile and a small hypothetical rocket were used. Key assumptions (introduced in section 3 earlier) are: (a) the robotic combatant can approach the target significantly more closely before releasing its missile than would be acceptable for a manned combatant and (b) the robotic combatant's shooter detection system will provide it with more accurate target location information. Table 4-2 summaries the key parameters and their values used in the estimates. The resultant plots for a range of C values are shown in Figure 4-4.

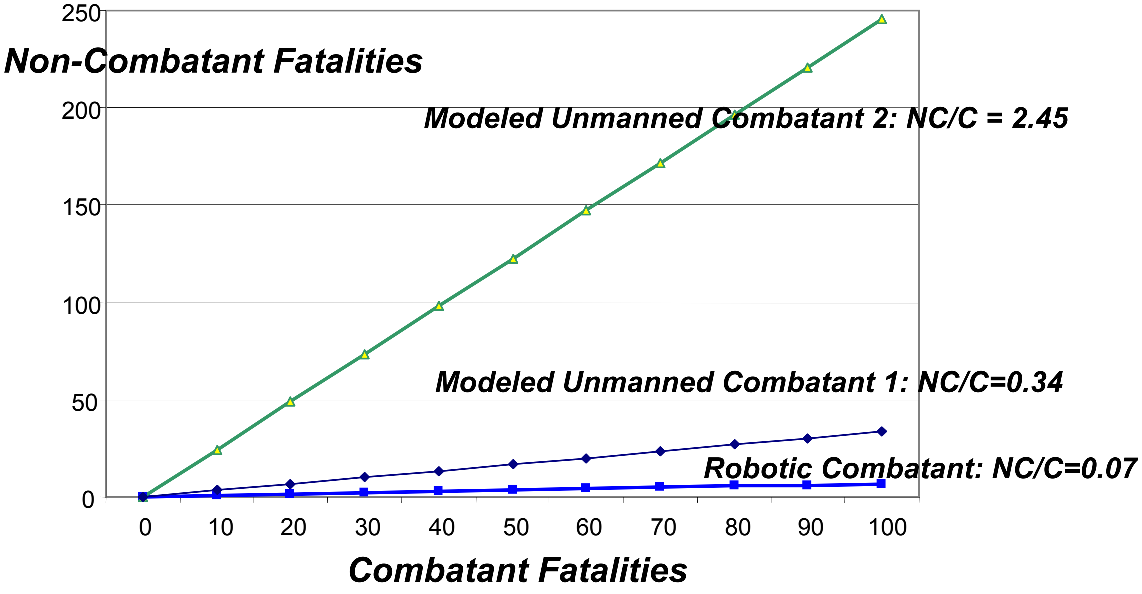

Figure 4.3. Combat robots may perform with NC/C ratios significantly lower than manned combatants, thereby greatly reducing the risk of non-combatant fatalities. A key assumption is a command and control strategy that effectively maneuvers the robotic combatants closer to the targets than would be acceptable for manned combatants.

Figure 4-3 shows the NC/C curves for the three cases that result from applying these parameter values to the parametric model discussed in section 4.3. Figure 4-4 shows the results for the best case of the manned combatant compared with the results for the robotic combatant as well as with the historically typical ratios of NC/C = 0.5 and 2.0. The comparison suggests that a robotic force can greatly reduce collateral damage while maintaining the same level of lethality toward the enemy combatants if it can meet three criteria: rapidly maneuver close to the target (thereby accepting a higher risk than would be prudent for a manned platform), localize the target with high precision using a network of specialized sensors, and use smaller munitions.

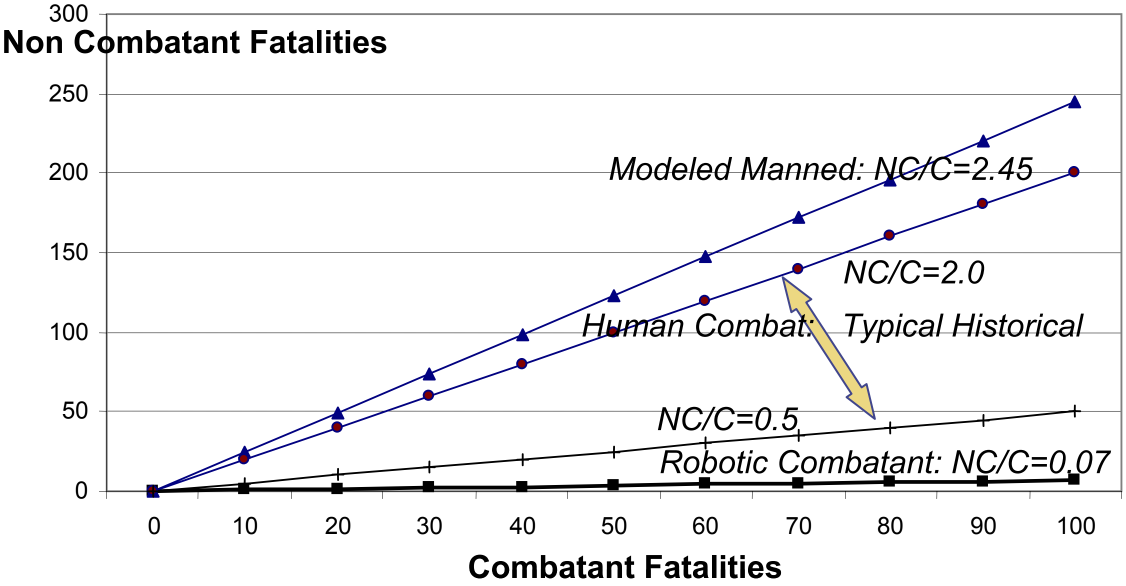

Figure 4-4. The proposed model estimates the risk of collateral damage caused by a conventional manned combatant comparable to the typical historical range. According to the same model, a robotic combat team could potentially reduce collateral damage well below the typical historical range.

5 Conclusions

The growing presence of advanced robotic combatants on the battlefield raises legitimate concerns about the associated risk of non-combatant fatalities. We outline a specific scenario in which such combatants might be used and where the risk of non-combatant fatalities could be potentially significant.

A key metric relevant to analysis of collateral damage risk is the ratio of non-combatant fatalities to enemy combatant fatalities. We present a model for estimating the NC/C ratio that accounts for a broad range of factors addressing the accuracy and impact of the weapons, the sensor capabilities, and the command and control effects. Significantly, the model suggests that robotic combatants can perform with dramatically lower risk of non-combatant fatalities as compared with conventional manned combatants, while achieving the same degree of effects against the enemy combatants.

Two assumptions are of critical importance to the above conclusion. First, robotic combatants can afford to come closer to the enemy fire sources than would be acceptable for a manned platform. The closer range allows more accurate fires and smaller weapons (with smaller blast radius) with less risk of affecting nearby non-combatants. Second, in our scenario the primary mode of operations of the robotic combatants is the revenge fire. Robotic combatants use a range of acoustic and visual signatures to identify and locate the sources of hostile fire more accurately and rapidly than a human would. This reduces the probability of an unintentional fire at a misidentified non-combatant or of a fire at a misidentified location of an enemy combatant. Both assumptions are consistent with recent advances in related R&D programs. It also should be noted that both assumptions are largely functions of a control and command system employed for the combat robots.

In order to obtain a modicum of validation for the proposed model, we perform an initial exploration of the historical data regarding the NC/C ratios observed in the armed conflicts within the last 100 years. Although our study of this aspect is of a tentative nature and does not claim the requisite methodological rigor, the findings appear to be rather remarkable: the historical data on NC/C ratios suggest a nearly linear relation, with a narrow range of the ratio values, in spite of the extremely wide range of the conflicts and absolute numbers of fatalities. The proposed model produces results that are generally comparable to the historical range.

More broadly, we seek to introduce and motivate a new area of inquiry in command and control research for combat robots: how to model, predict, and *minimize* the non-combatant fatalities while maintaining effectiveness of the force against the hostile combatants.

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