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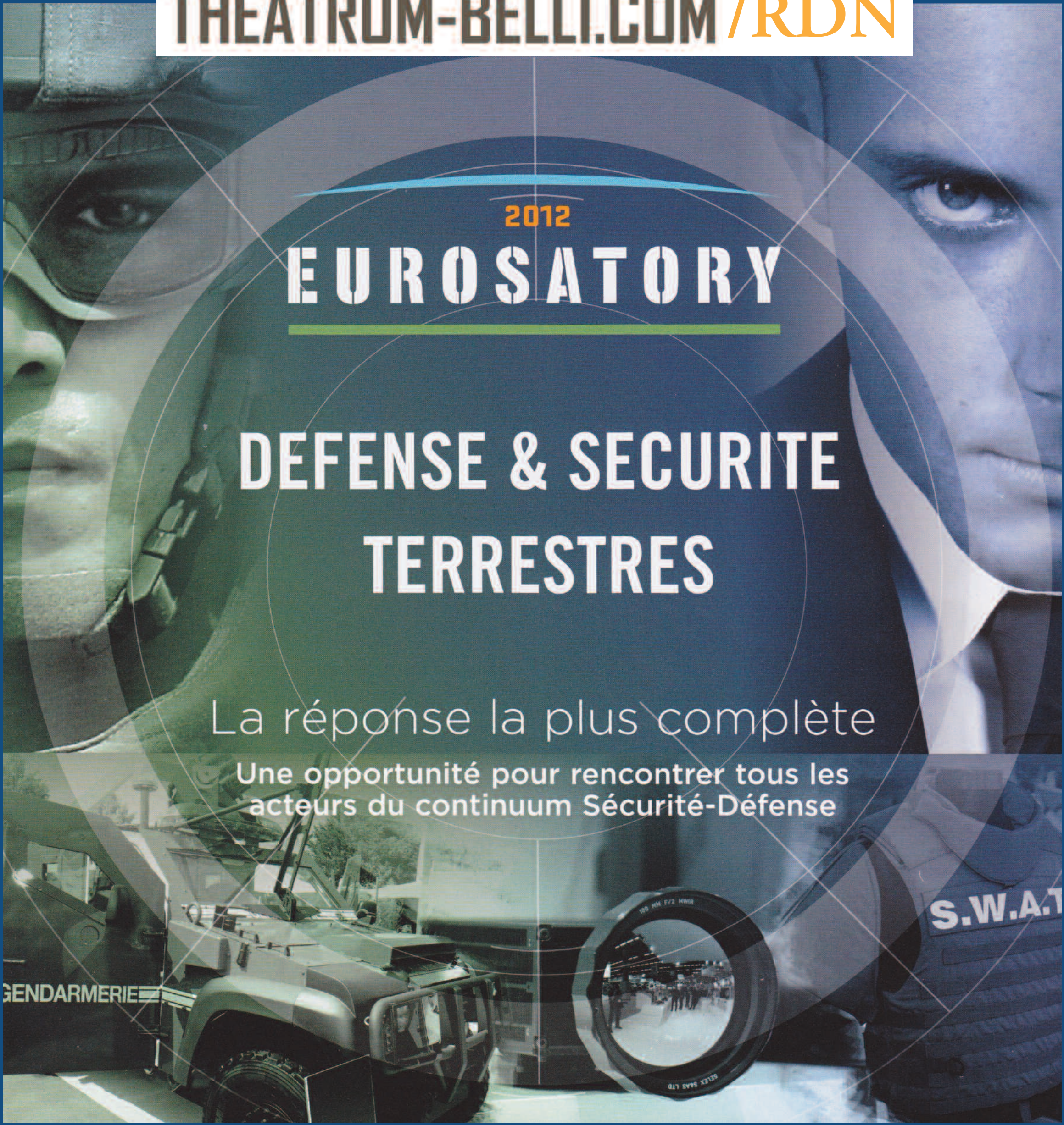

Combat robots

Reducing the logistic footprint

Armour of the future

Les Cahiers de la
Revue Défense Nationale

Eurosatory 2012

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Eurosatory 2012, june 2012

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Preface

This special edition is produced in cooperation with *Revue Défense Nationale* and appears on the *Theatrum Belli* blog. Modern means of communication seem those best suited to broadcast what our researchers are up to and what our industries are producing in these fields: all is rather technical but it shows the degree to which these people are involved in the daily life of our armed forces on operations.

And it is precisely for this reason that they have been selected.

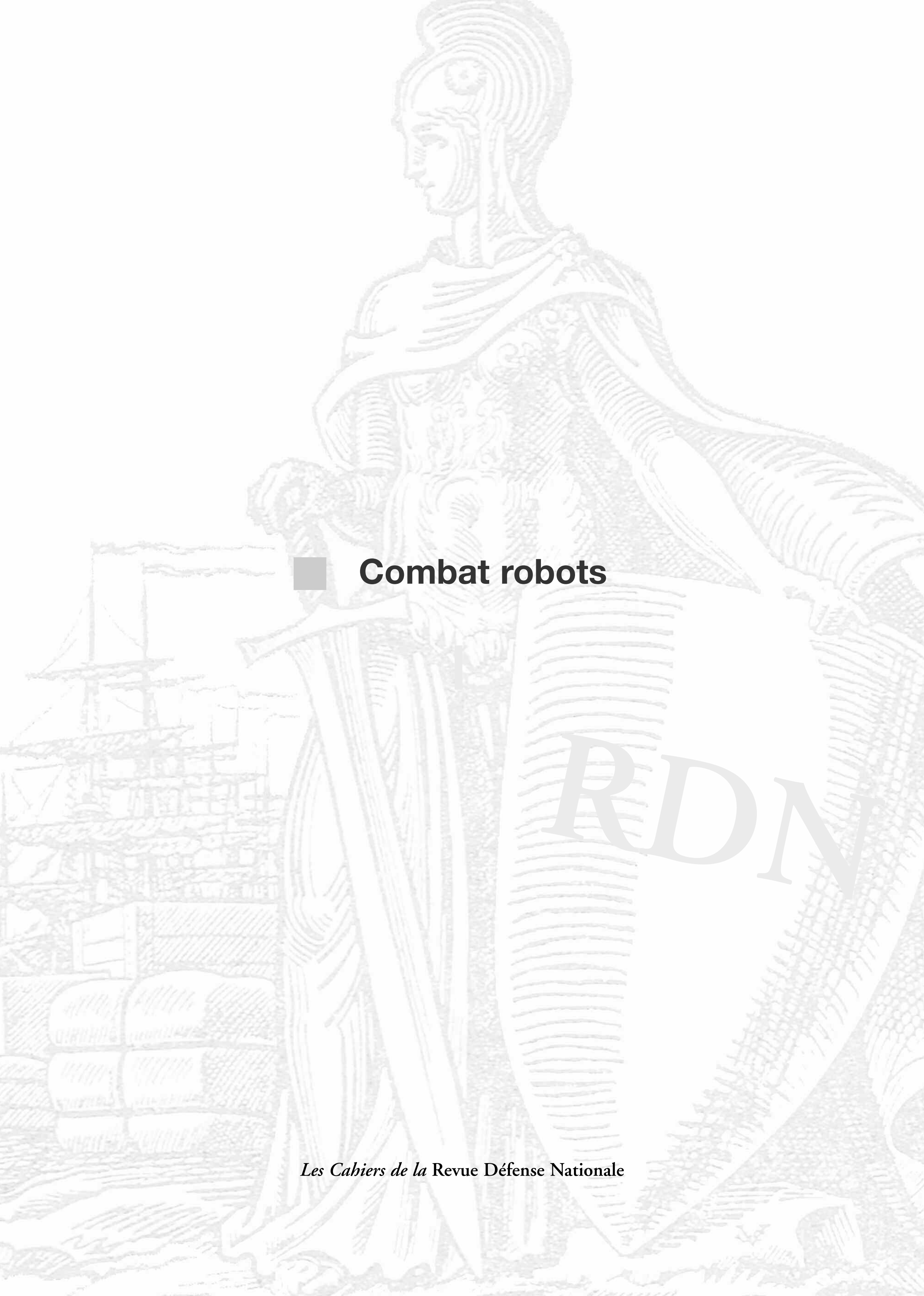
It is almost impossible talk of military technology in the current decade, from 2010 to 2020, without raising the subject of armed combat robots. General Yakovleff's articles on the principles of design and use of robots have already appeared in RDN (in slightly abridged version in English), and we believe it important to reproduce them here to set the issue in context. Darko Ribnikar, of Cassidian, brings the point of view of a company-based researcher and describes the basis of what an autonomous or semi-autonomous battlefield machine might be like, together with the technological and social implications of its use in service.

Future armour design is another of the preoccupations of the fighting soldier, and rightly so. The increasing use of improvised explosive devices, IEDs, in recent operations and the drift of our style of warfare towards counter-insurgency are pushing the issue of protection higher on the agenda of Western societies. The debate began in 2002/3 among US forces in Iraq and has greatly broadened since then. Here, we are not talking of the scientist Cosinus's ideas on detection of IEDs but of how we can provide our combat troops with the means to survive such attacks. Bruno Mortaigne is a researcher for the Direction Générale de l'Armement, and his impressive article is an exposé of the state of the art in this specialised field. The latter is further illustrated in the article by Messrs Petitpas, Vallée and Bettencourt of Nexter, who give us a technical analysis and description of the possible development and production routes that were highlighted in the previous article.

Finally, we take a look at a particularly hot topic, given the impending withdrawal of French forces from Afghanistan: reduction of the logistic footprint. We feel it important to reproduce here the recently-published article by Jean-Paul Lafitte on the issue, given the broader current situation. Thierry Veisemburger, also of Cassidian, offers an accurate and realistic analysis of the principles that must drive modern military logistic design, on the basis of the information and CAD systems that aid them.

In sum, we present you here a collection of articles that examine attack, defence and support, following the classical principles of the military art. You will see that intelligence is missing: this does not signify disdain on our part, merely that the subject has been amply covered elsewhere

For *RDN*, General François Chevant



Combat robots

Robots on the Battlefield
Towards a new combat system
Part 1: Design choices

Michel Yakovleff

General, SACEUR's representative on the NATO Military Committee.

One thing as sure as war itself is that every technological development has an impact upon the field of battle. Just as iron replaced bronze, and steel replaced iron, the development of chemistry gave us incendiary weapons like Greek fire, then explosives, and later, along with the development of metallurgy, it led to the invention of firearms. Mechanisation swept the horse from the battlefield and opened up the third dimension. The list of examples is endless.

Today, miniaturisation, computerisation and other technological advances are allowing the development of robots, whose capability and number seem to be increasing exponentially. The question is not whether the introduction of robots onto the battlefield is desirable or not, but rather of the timescales and circumstances of their introduction. Unless we look at it that way, we risk a re-run of the sterile arguments between mounted cavalry and supporters of motorisation at the end of the First World War. And yet accepting the inevitable is often far from pleasant: the clear danger is of removing man from the battlefield. It is possible to conjure up a picture of completely autonomous robots eventually waging war against each other on behalf of humans, yet without the presence of the latter. Whilst that is perhaps a dream of future warmongers, it is not a future most of humanity would choose. Any discussion of widespread automation, or robotization, of the battlefield must always bear in mind this major moral and conceptual reservation.

What is a robot?

Insofar as we are considering it in the present context, a robot has three principal characteristics:*

- It moves under its own power–at least for the majority of its missions. It is an autonomous device, both mechanically** and in terms of decision-making.

*** Robot terminology**

The French Military Staff define a robot as a reusable mobile ground-based platform fitted with captors and effectors (ie it can both detect and do), intended to perform elementary tasks in the ground domain with a certain degree of autonomy. The aim of ground-based military robotics is to allow the soldier to concentrate on the task(s) which he alone can perform, whilst the robot accomplishes certain well-defined tasks in support of, or in place of the soldier.

**** Mechanical autonomy**

It does not need to be pushed, pulled, towed, carried, launched or thrown, at least for the majority of tasks it is likely to be called upon to perform.

- It acts, in the sense that it has a function other than the ability to move (for example, it observes, or carries or pulls a load). This is important to note because in modern robotics, many robots have no function other than to move. Here, we will discuss robots with other operational functions.

- Above all, a robot has decisional freedom, which means it adapts its behaviour to its environment in some manner that has been more or less predetermined by the algorithms installed by its designer.

Some machines move, yet remain under the control of a 'pilot', such as drones, or robots used by mine disposal teams. In such cases, and within the bounds of this discussion, the term robot is incorrect. A remotely-controlled device, however sophisticated it might be, is not a robot. At the other end of the scale, machines exist that are entirely autonomous but do not move, a mine being the most basic example. Within this group is the family of independent, 'abandoned' detection devices: the sole difference from a mine being that they transmit information instead of exploding. In this case, it is the lack of independence of movement that excludes them from the family of robots.

The autonomy of a robot

By definition, the robot has an autonomous perception of its environment as well as a capacity for reasoning and decision-making by interacting with that perception. The decisions it takes flow from predetermined algorithms, but limit human intervention as far as possible–without which we would be back with a remotely-operated device.

As a general principle, the more autonomous a robot, the more use it is precisely because that autonomy lightens man's workload, in the same way that the more a guard dog knows how and when to act, the more useful it is.

Through the use of artificial intelligence technology, we know how to design and simulate objects that are capable of executing tactical missions autonomously. They put a set doctrine into practice, apply the necessary know-how for the mission, recognise and take into account their environment and their opponents, and store and apply the lessons learnt from their operations by the use of feedback or recycle loops. For example, in simulation we have learnt how to build an all-arms unit whose tanks and crews fully understand the main effort, are alerted if they reach an obstacle–at which they look for a way round whilst still ensuring cover for the unit during the search–can bridge a ditch, then cross it and return to the ordered course in continuing pursuit of the mission. Should they meet the enemy, they open fire, call for support, take cover and manoeuvre as needed.

We have known how to do this on computers for some ten years-or-so, and very credibly, too, to the extent that these programs allow human background input operators to be replaced in staff exercises, thus economising on the personnel required to create the tactical inputs needed to update the players on events and results of combat. Thus there is no conceptual barrier to be overcome in order to apply these algorithms to physical objects operating in the real world. The robot that we will soon see on the battlefield (if it is not there already) is therefore capable of receiving a mission order and executing it without any more interaction with its human master than the man it is supposed to replace. This would be the first criterion of effectiveness that would justify the choice of a robot in the place of a man: at the very least, it has to return equal performance for the majority of the mission.

The limit to its autonomy is very clear if the robot in question has any capacity for aggression: it must not be able to fire in the absence of a positive order. Once again, the comparison with the guard dog is pertinent: when he perceives a threat, the well-trained dog gives a signal to his master by growling, flattening his ears or adopting a certain posture, but he waits for an explicit order before attacking. On the other hand, the robot has to be able to protect itself without reference to its master, for example, by taking some evasive manoeuvre. Depending on the robot’s construction and flexibility, it could take a backward or side step, or some other defensive move, rather like the man who flattens himself on the ground when under fire. It might, for example, spread itself out to limit its vertical profile or, on the contrary, stack its various ‘organs’ vertically to allow it to hide behind a post. From this point of view, a form of modular construction inspired by Rubik’s cube might seem a worthwhile path to explore.

Making best use of a robot

In order to justify the necessary investment, robotization of the battlefield must give real added value either by allowing man to do better those things he can do (or to do them differently), or by doing something else altogether. This ‘something else’ has yet to be invented, but is certain to be invented, just as the development of information technology has given rise to uses and needs unimagined at its outset.

For reasons which will be explained in later articles, it is considered that combat robots will give the best added value in urban operations, at short range and when accompanying a platoon in the theatre. This does not exclude the value of robots in other functions and with an operational range far in excess of that of infantry on the ground, but for Western forces, which are always facing a numbers problem and are therefore careful to protect their troops, priority will always be given to the most unstable and risky situations.

Robots could be given three distinct roles: captor, effector (or aggressor) or servant (logistics). Following the reasoning that will be presented later, it is postulated that these close-range robots would in the main be dedicated to the detection role, leaving a considerable proportion of their brethren in the servant role. The aggressor robot would be somewhat more marginal. Nevertheless, this does not follow today's thinking, largely because much of current effort is on aggressor robots. We think this priority is erroneous.

The central problem is that of detection and discrimination. No robot can detect and identify hostile intent. What it can detect is recent or current presence and movement. In order to be able to discriminate, cross-checking between the various sensors is a determining factor. Hence, when we think of robotization of the battlefield, we have to think of robots in the plural–even a multitude of them. The first job of these numerous robots is to broaden and deepen the area of capture of information, ahead of the troops, of course, but also on the flanks, at upper levels and in basements.

The first conceptual conclusion is therefore that the very concept of robotization of the battlefield necessitates a multitude of robots, which we consider would be mono-captors of small dimensions.

It is easy to imagine the number of personnel that might be required to control this multitude of robots, even taking into account recent tactical experience. These robots therefore have to be independently autonomous once they have received their mission, but more important still is that they be collectively autonomous. This is swarm behaviour, in the language of artificial intelligence: each component has considerable freedom of action, in particular to ensure its own survival, but each decides the action to be taken in the broader context of the group. Thus a multitude of individual wills is integrated into a collective will.

The second conceptual conclusion is that robots will operate in swarms. Consequently, the development of battlefield robots is not conceivable without development of individual and collective algorithms that will govern the mission. It is important to start with the latter, before developing the machines themselves, rather than to follow the opposite logic of first developing the robots and only then making them work together.

The impact of combat robots on future combat

To take it further, it is easy to see how a reconnaissance platoon, or one conducting surveillance on a sector, could act more quickly, and its troops be in greater safety, if it is surrounded by a swarm of captors. Although the risk of tactical surprise cannot be eliminated, it would be greatly reduced. Moreover, a surveillance swarm would allow the human element of the platoon to focus its attention on the most dangerous sector, and economise on watching the rear and the flanks, for example. The ratio of troops dedicated to the main combat would be improved. In the knowledge that a moving section keeps 30 per cent of its manpower in second echelon to cover the rear and to supply a manoeuvre reserve, elimination or reduction of this need would clearly lead to a more favourable offensive ratio.

Logistics is a great consumer of manpower, and the nearer to the front it is, the more manpower it consumes. As a result of mechanisation, large logistic bases in the rear require little manpower–to operate sorting and packaging machinery and fork-lift trucks in particular. It is easy to imagine massive robotization of this function: it would free up few personnel, but the advantage remains significant. On the other hand, transferring fuel from tankers to jerrycans, and then carrying these jerrycans to the front, simply eats up personnel. What is true for fuel is also true for munitions and victuals, among others.* Removing a wounded person to shelter occupies some ten men for one to two hours. Although medical action remains privilege of man to administer, the entire mechanism of transport to the rear could be given to robots. It is in this kind of work that robotization would allow us to do better.

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During the first battle of Grozny, in the winter of 1994-95, one third of all manpower in the town was employed on logistics at the front, and in particular by transhipping of stores. A serious consequence was that these soldiers, even though brought back from combat, were unable to rest because they were employed on logistics operations. Wear and tear of troops, physical but especially psychological, will weigh heavily on the battle.

To do things differently, much remains to be explored in order to discover the combat possibilities offered by this new robotic ecosystem. And since we have established that artificial intelligence will be its determining factor, this exploration can start today in simulation mode before we even begin to think about machine design: operational research should progress before the development of devices. Such research is not so difficult, and is sure to be crucial to exploration of more exotic applications, removal of doubt and confirmation of opinion. The most likely outcome is that the reduction of the factors of uncertainty, and of the tactically unknown that weigh upon every soldier groping around in search of the enemy, will fundamentally change his aggressiveness and rate of tactical progression outside the contact zone. Currently, the speed of advance when threatened by a probable enemy presence is reduced by the need to maintain a reserve ready to act as soon as that enemy is discovered. Once the unit knows with greater certainty that it is not threatened, and thus finds the enemy earlier and with greater precision than before, it will achieve greater speed of manoeuvre. Its task organisation will certainly be modified as a result of the improved ratio of immediate combat and second echelon troops, the latter ready to act in case of the unexpected. In the longer term, these changes will also have an impact on the contribution from each arm. In the same vein, all of the troops will be able to benefit from a rest period or an operational pause, and to sleep soundly without the need to set watches, once they have established sufficient confidence in their robot escort. In the knowledge that, in general, ten per cent of manpower is used for security, here again is a situation in which a significant proportion of potential is saved and can be redeployed on other tasks.

The moment will certainly come when new ideas will be born, that we are unable to imagine today. When the first computers were designed, they responded to the need to manage vast quantities of data. Nobody even imagined today's office applications–let alone computer games. It would be fatal to apply this logic again. The more imaginative will gain a significant advantage, which in turn will seriously destabilise the more reticent. There again, operational research will prove fertile ground.

One line of exploration sure to be followed is that of warfare between robots. The history of aviation provides a good example of this. In the beginning, aviation was a means of observation, and pilots waved at each other whilst accomplishing their missions. Then one fine day, one of them took into his head to repel an intruder, so he drew his pistol and fired at the other, in doing so unleashing an escalation and a specialisation which continue nearly a century later. Today's fighter aircraft are the most symbolic sector of modern aviation. It is therefore a pretty safe bet that two robotized troop units will one day have each part of their mission to eliminate their adversary robots. From there it is a short step to imagining that the day will come when the human combatant might be tempted to leave the robotized battlefield to the robots alone. And there, we come to the ethical limits of this exercise, which should be explored with healthy scepticism.

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Robotization of the battlefield is likely to see the emergence of an ecosystem based on robots operating in swarms. The development of artificial intelligence will be crucial to exploiting the potential of these machines. Operational research, both now and in the future, has a contribution to make in determining their desirable characteristics, as much for each individual device as for their collective action in the service of, and alongside humans. This operational research must precede the development of the machines themselves. In the next part, we shall examine the most likely physical characteristics of these robots along with how they might be controlled.

Robots on the Battlefield
Towards a new combat system
Part 2: The major characteristics of robots

Michel Yakovleff

Function: aggressor, captor and servant robots

The first thing to establish is that in view of current and likely future technology, aggression is not one of the problems that designers will have to face. We already know how to kill and neutralise from any reasonable distance and to do it with an accuracy that will soon reach its practical limit. We also know how to minimise collateral damage with the right weapon at the right moment, so increase in accuracy is no longer really needed. Hence at least in an initial phase of using robots on the battlefield, we might reasonably presume that they will fulfil one of the functions of aggressor (the armed robot), captor/sensor or servant.

From the outset it seems that major use of an aggressor robot is questionable, albeit not completely impossible. As mentioned in the previous part, man has to be included in the decision loop to ensure discrimination and proportionality. Furthermore, mechanical issues come into play: the complexity of a firing platform, coping with recoil, target discrimination, reloading and so on. As things currently exist, the law of diminishing returns means that man, or a remotely-piloted machine under control of man, remain the best firing platforms. One might therefore anticipate non-lethal robots armed to break down doors, or to lay smoke screens, for example, as the most likely of the aggressor type. On the other hand, in environments in which man cannot fight in the long term–contaminated zones, for example, or under water–aggressor robots are of much greater interest. Yet in just one example, protection of oil platforms, it remains questionable whether robots designed to keep divers at bay are of any greater use than a miniature torpedo launcher fixed to the leg of the platform and operated from the command bridge or some other remote position.

This illustration leads to the conclusion that new or complex situations do not of themselves justify the invention, even less the use, of robots, and that it would be better to look first at proven solutions. Robotisation is not done just for fun, but to respond to the absence of any other solution.

The captor robot seems to be the principal way ahead, at least in the medium term. It adds an undoubted value to intelligence gathering for the troop formation, rendering it possible in areas where men cannot penetrate, or can only do so with difficulty or at high risk. We already have the technology for optical, acoustic, seismic, radio and radar sensors which operate way beyond any human capability, and by developing mass spectrometry technology we should in the short term be able to produce ‘sniffer’ robots that can identify chemical components in the air, the soil or deeper underground, thus localising buried explosives or chemical contamination. With seismic detectors, sensed changes in the soil structure might identify buried mines or electrical cables. All these technologies exist and their miniaturisation ought to be possible in the near future at low cost.

The servant ‘robot’ has existed for many years in the form of the pack-horse that carries man’s loads over mountainous territory. Today’s mine-destruction robot is not a real robot in the context of this article (see the definitions in part 1) but there might be value in rendering it autonomous in certain conditions. Logistic operations have already been noted for such robots but another use might be as a radio relay, penetrating well behind enemy lines. That said, is there any real need for robotisation of such a function? A re-transmitter could just as easily be launched as a sub-munition of a missile, or dropped from an aircraft, in which case it would consume none of its own energy in getting there, unlike a robot which might need to travel a long distance under its own power, quite apart from the risk of detection or being ‘turned’ in the spy sense of the word.

How big are these robots?

Size is clearly a function of the robot’s own function–the size of its armament, its sensors or the load it has to carry. For aggressors, unless there is some significant technological breakthrough, they are unlikely to be much smaller than today’s remotely-operated platforms because of the need for 3-axis stabilisation. In the case of a robot carrying a medium-calibre machine gun, or an anti-tank missile launcher the size might be half that of a conventional manned machine, largely because of the absence of the space needed for the crew. But between a remotely-operated device and a robot the size difference is negligible, the main difference between them is the presence of algorithms that make the robot autonomous. All other advantages result from miniaturisation, and not robotisation.

This is all the more notable with captors, where miniaturisation is advancing rapidly. Cine-cameras already exist that weigh just a few grams and can fly in machines the size of a large insect. Other sensors will soon follow this trend, even if they do not reach the extremes of optical miniaturisation. As stated before, for reasons of simplicity and reliability the captor robot will generally be a mono-sensor. There will be a great temptation in the early days to fit several captors to the same mobile platform and yet this seems to be the wrong path to follow since the complexity will not lie in the sensor itself but in the platform and its survivability. The first generation of functional captor robots are likely to range from the size of a mouse to that of a large dog–the median size being that of a cat. From this there will be considerable tactical consequences, of which more later.

Servant robots can be larger, since their main function will be to carry loads. Sizes from a large dog to a mule are possible in combat zones, with much larger ones in the rear. At the higher end of the size range, there is little to be gained by robotisation over a piloted vehicle, manned or remote.

What will they look like?

Smaller robots in particular are likely to take their shape from nature. Indeed, certain flying machines, especially those designed for long-term stationary flight, already take their inspiration from insects. Underwater devices used for work could be shaped like an octopus, whose flexibility allows it to penetrate everywhere and exert a force disproportionate to its own weight. A prototype, already under development, will permit a future robot to open or shut a submarine valve. A device that has to infiltrate anywhere, but without any need for speed, might well resemble a centipede or a snake, and small ground-based robots might adopt the form of a spider, permitting a compromise between ability to move and, if needed, the ability to jump and glide – the legs becoming ailerons in the latter case, and the jump initiated by jets of gas or compression of the legs.

Operational range and speed

It is theoretically possible to design ground robots capable of long range and endurance–over hundreds of kilometres–following the logic that led to the development of the drone. Indeed, successful trials have been conducted in the United States. And yet nothing will replace man's intervention in matters of intelligence gathering and the judgement needed. Robotisation of the task could well involve much more manpower and thus be less efficient. On the other hand, radiological reconnaissance, for example, in a contaminated zone without opposition (= no enemy) is today's reality. After the tsunami in Japan, for example, radiation monitoring in the contaminated zone could have been allocated to such robots. And yet we already know how to do most of this today with existing devices and drones, and proven technology. It is therefore open to question whether expenditure on robots to do the same tasks is justifiable. Once again, another demonstration that the possible, even at a reasonable cost, is not necessarily the ideal solution.

The speed of advance of a robot has two elements: sprint speed and tactical speed. Sprint is needed for the final 'leap' or to evade a threat. A problem lies in the energy profile of such a machine: instantly achieving a high speed, though for short duration, requires a very different set of characteristics from slowly gaining that speed and maintaining it for a long time. Tactical speed is the long-term speed needed for the duration of the mission, and oddly, perhaps, the energy requirement is less. An infantry platoon moves at 3 kph, and fights at just 1 kph, taking into account all that it has to do during such movement. Hence an accompanying robot has no need to travel at 60 kph: even though it might be useful if it could achieve that speed for a leap manoeuvre, it has no need to maintain it for minutes on end. If for some reason the platoon should travel at 60 kph, then the robot will travel with it in a vehicle and later disembark with the troops to continue ground combat. In practice then, a robot that is designed to accompany man will be generally adequate if its sprint speed is about that of a dog. The tactical endurance of these robots does not need to be any greater than that of the troop unit they support – we might speak of a few hours at a time, or a day at most, since the need for rest and sleep of the troops allows for recharging of the robots' batteries or their refuelling.

The stealth problem

By improving current technology, smaller robots, travelling on the ground can be made nearly silent and therefore discreet, at least in the normal noise of the urban environment. On the other hand, in the silence of the night, or in a dead town, much more progress is needed before a swarm can be made undetectable at short range: this is essential for intelligence gathering. It all gets more complicated for airborne machines, in which sound-deadening is very voluminous and saps energy. Advances are being made in reducing aircraft noise but the silent aircraft is a long way off. This is not just a point of detail but is an essential issue to be included in the definition of the device and not left as a consequence of other technological choices: it is very hard to remedy a sound fault that is an original design sin. In deed, it is possible that the acoustic signature of robots of all types may turn out to be the major technological obstacle to be overcome, in turn delaying the introduction to service of this new family of machines.

Robots on the Battlefield
Towards a new combat system
Part 3: Tactical, psychological and ethical consequences

Michel Yakovleff

We have seen that it is generally accepted that future ground combat will in the main be in an urban environment, surrounded by the population, and against an asymmetric enemy that mixes with the population at the very least up to the point of actual combat, and quite possibly during and after it.

What use are robots in such a context?

In the previous part it was postulated that the most widely used robot would be the captor type, generally a monocaptor, acting in a swarm in support of a troop formation. The troop would be preceded by several robots whose multiple and overlapping angles of observation would cover all sensor types–visual, seismic, electromagnetic and gas analysis, among others. Further machines on the flanks, and even in the rear, would ensure safety at a predetermined distance as a function of the threat and the human environment, which is not necessarily hostile. In the urban milieu, it would be useful if the bubble so deployed could observe the high levels, hence the interest in a capacity for climbing and seeing over a vertical wall, or even jumping from wall to wall. The surveillance deployed might also extend to the underground domain, with small-sized robots using underground conduits of all sorts and being able to operate in water.

The master-robot link

It has already been shown that it is pointless to claim to be able to control each element individually, hence the need for artificial intelligence. To limit the need for human input, dialogue between the components must also be autonomous: for example, with artificial intelligence ensuring constant optimum captor coverage, a robot could automatically change sides of the road to cover a blind spot of one of its brothers. In the same vein, and even if it seems counter to logic, robots should not convey real-time information to the human controllers: only in the case of an alert, and then according to some predetermined filtering algorithm, should information be transmitted. In other words, the moving troop formation will in general be observing with its own eyes and not those of the accompanying robots, although of course, man should always be able to call upon transmitted imagery if needed.

One major limitation to the deployment of a swarm is the bandwidth needed to pass the mass of information to and fro. It must also be protected as it will, almost on principle, be attacked and, although posing a serious problem today, it will certainly be overcome eventually. But as a result of this, the concept below is expressly intended to minimise the bandwidth requirement, at least outside the active phases of combat.

A three-stage dialogue between human and robot

Routine: no danger detected. In this mode a single operator is ideal, letting the swarm operate with little external input. The swarm keeps pace with the troop according to the mission criteria.

Alert: some detection made. The swarm adopts a guard posture and the troop interrogates the appropriate captors, each soldier attending to ‘his’ robot to analyse the information. The commander interprets the result using collective artificial intelligence.

Manœuvre: according to the interpretation of the detected information. The commander might modify the captors’ tasking to gain further information in a particular sector. Each such use adds to the collective bank of artificial intelligence to improve future contact analysis.

This leads to a counter-intuitive, though crucial conclusion, that the dialogue between the robot and its master must be an absolute minimum. In real terms, the three-stage dialogue is that to follow, according to the circumstances.

Some tactical ideas

Up to now we have considered front-line combat, on foot and in towns. On a basic level, the pawn in this game is the platoon of men (say, around thirty) accompanied by its robotic ecosystem which provides most of the intelligence and perhaps an element of logistics. Quite apart from the fact that what it takes thirty men to do today will probably be done by fewer in the future, whatever happens, if the same platoon were to be robotised, the same tactical effect could be achieved by, say, ten or fifteen fewer men. That said, reducing personnel numbers has a limit in that even in an environment of super-efficient artificial intelligence, there will still be a need for one man to control one robot in order to observe it, to assess the data it returns and to manoeuvre it if required. After all, a dog handler only controls one dog. So, if indeed the captor robot is the preferred way ahead, it seems more appropriate to turn the logic on its head and maintain the number of men (which is in any case reducing in Western forces for other reasons), since in that way combat in the true sense of the word will remain man's privilege. Hence for a given number of men, robotisation will considerably improve the effectiveness of a unit in modern conflict, be it asymmetric or not.

A company that has three or four of these platoons should then have an anticipation capability for use by all of them and an ability to expand search areas. For all that, a similar observation capability exists today in drone aircraft. Some of these could be robotised (which means be made autonomous) although the added tactical value in doing so is not convincing: the only thing to be gained is improved aerial observation and communication (including intercept) ability at a few tens of kilometres range, for a longer period–all of which are available today.

The conclusion has to be that robotisation of the battlefield will give best added value in close combat and in contact, and not in some long-range, long-duration, broader context, which does not appear efficient seen from today's perspective. Precisely how this robotised unit will be deployed in an urban environment and in the presence of the population remains to be seen. Which brings us to the psychological and ethical aspects of this new capability.

Psychological aspects

In general terms, the psychological aspect of the use of robots lies in their acceptability. The robots we have spoken about, that might accompany troops, or the 'spider' robot, do not yet have any fixed form, nor are they necessarily going to be welcomed, whatever form they may have. Even one in the shape of a cat or dog has no guarantee of being welcomed with open arms, and just imagine the reaction to one shaped like a snake or an octopus! We should not forget that these machines are likely to be noisy, too–at least in the early stages of their development.

Today's soldier looks not unlike a wasp (Which is, by the way, an Iraqi slang term for coalition troops!) from a cartoon strip: he is already disliked by the population at large, with his carapace of armour, helmet and dark glasses, and the mass of equipment that he carries disguising his human profile. It is nonsense to believe that such dislike, rejection even, is cultural, in the sense that Afghan or Iraqi populations have difficulty in accepting the intrusion of these Western soldiers, since the very same soldiers in the same garb and with the same attitude on the streets of their own capital city would hardly be any better viewed or accepted. The growing visual gap between the soldier we see and the real man behind the mask, as it were, is already a major psychological problem. Imagine how that problem will be accentuated when this soldier, already resembling an extra-terrestrial, is surrounded by a buzzing, bouncing, crawling, squealing and whistling swarm of robots ahead, above and behind him!

It is a pretty sure bet that our ‘robotised’ platoon of troops will encounter considerable difficulty in achieving calm and friendly contact with a sceptical or unconvinced population, let alone with a hostile one. In such cases, robotisation could be a disadvantage or, at least, a major constraint, necessitating significant tactical changes to counter the effect on the mission of the negative psychological effect.

Ethical aspects

Up to here the perspective has been purely technical, but warfare is a human concern and must remain so. We have already established that a long-range robot (according to our definition) is conceptually nonsensical, which from the ethical point of view is a good thing. Indeed, if we were to imagine a squadron of robots bent on attacking the enemy’s rear formations with no, or almost no, human intervention, it is quite conceivable that the enemy would design other robots to protect his rear and counter infiltrators, be they human or machine. In such a case, we would end up with a war of robot against robot on behalf of humans but without the latter. This would be a totally new vision of warfare and, in reality, horror beyond belief.

The advantage of the robot accompanying the infantryman at the latter’s pace is that the soldier cannot escape from his ultimate responsibility. The swarm will probably be seen as an appalling development in warfare but it does not denature it to the same degree as the squadrons of bloodthirsty robots described above.

The writer Isaac Asimov’s three rules of robot ethics in essence declared that:

- A robot cannot attack a human nor remain passive if a human is in danger;
- A robot must obey human orders unless they conflict with rule 1;
- A robot must protect itself so long as such protection does not conflict with the first two rules.

It is clear that the combat robots we have been discussing break all of these rules from the outset of their design. Nevertheless, the search for ethical use could well start from Asimov’s basis.

The first thing to note is that ‘our’ robots are not just simple machines: they have considerable decisional autonomy in their design, which is in fact their primary advantage. But decision is inseparable from responsibility. Remember, a dog handler remains responsible for his dog’s actions, so how should we reconcile the decisional autonomy of robots with the necessary responsibility of their masters? However complex a robot’s behavioural algorithms, human responsibility is committed on three levels: the designer (especially he who shaped the artificial intelligence); the tactical commander, who decides the mission, troops and limits (including ROE); and the individual robot controller (the 'master') who has the direct command link with the machine. Thus the training of a robotised platoon must necessarily include a considerable amount of training on the ethical use of these machines which explores the moral limits of their deployment. Quite apart from the aggressor robot, which clearly contravenes Asimov's rules, even captor and servant robots push the limits of his laws once it comes to self-protection.

As a general rule, self-protection might be thought as countering an innocent gesture or one of passing malevolence, such as that of an inquisitive child or an angry passer-by, as distinct from a true adversary who knows exactly what he is doing. The simplest and probably least dangerous protection from the innocent gesture is a dodge manoeuvre, the robot remaining essentially where it is and on task. Such a 'dodge' could simply mean adopting a less vulnerable form, playing on the ability to change shape that has been mentioned before, perhaps as a hedgehog rolls into a ball to protect itself, or, for 'jumping' robots, it might simply be a question of leaping out of the way of the gesture and creating distance between the two. A further stage in this defence could be a capability for non-lethal reaction, rather like the hedgehog which erects its spines, the electrical discharge of some fish or the emission of foul-smelling gas. When faced with an evidently hostile act however, most robots will be very vulnerable because of their power-to-weight ratio: an armoured robot that is capable of surviving a machine-gun burst will have little or no agility. Protection of the system will therefore lie in numbers–the swarm can afford to lose one or two of its worker bees and a positive attack on a robot will be seen like any other as a signal for engagement of the human element of the troop formation.

But let us get back to the population: people might take up arms against robots without intending any direct provocation against other human beings. Imagine an angry shopkeeper who destroys a 'spider' robot in his doorway–should he be arrested? If so, what is the legal justification for doing so? Or if hooded demonstrators armed with baseball bats attack surveillance robots near a checkpoint, what are the acceptable options for a troop of soldiers? Ethically, should troops be permitted to fire on a crowd of people in order to protect a robot?

Round-up of conclusions

- Robotisation of combat is with us, and developing.

- It will principally be used in small-scale combat operations, in urban environments, rather than on long-range or long-duration missions.

- Use of captor robots is likely to dominate, supported by servant robots and, in certain cases, the aggressor type.

- Robots will probably take their forms from the animal world, something that will have material, functional and, more importantly, psychological consequences given natural human reaction to certain animal forms as well as to the very concept of robots itself.

- The majority of robots are likely to be of small size, limited range and endurance, but with considerable ability to overcome obstacles, generally through jump manoeuvres.

- Robots will operate in swarms.

- Development of the swarm algorithm must precede the definition of each individual robot.

- Before robots enter the battlefield, great thought has to be given to their ethical use, which will, in turn, affect technological and cybernetic thought and design processes.

Ground-based robots: between reality and fantasy

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Robotisation of the battlefield is under way. Its steady march can be seen in the number of drones, principally airborne ones, now in use. These aerial systems are now working alongside hundreds of terrestrial vehicles which are bringing significant help to troops on the ground. The Americans are the main users, and from their point of view this evolution is real and impossible to stop. The immediate consequence is the great number of issues raised regarding how we should conduct armed conflict now and in the future. Often the first image that comes to mind is that of the *Terminator*.

And yet the robotisation of the battlefield as we currently see it is a myth, an illusion. It does not exist, because the machines used by troops are not robots but remotely-operated systems that have no ability to make decisions or to act alone. It is true that most drones, like most aircraft, can fly on autopilot, but the decisions that count–those concerning direction of the sensors and the use of effectors (for those machines that have them)–remain the exclusive responsibility of man. Regarding ground equipment, the situation is even simpler: the systems used by bomb disposal teams, for example, have no autonomy whatsoever as they are driven by man. Man decides and acts *via* these machines.

The truth is that there are no ground-based robots on the battlefield, just systems that are remotely guided and operated by humans. Nevertheless, some requirements, such as that for ground units to cover ever more terrain with fewer people, are sure to change the scene significantly. If to that we add our aversion to military losses, then the 'autonomous' solution has a lot of sense. But how soon is this likely to happen and how? Is the *Terminator* already being prepared in some secret laboratory?

What is a robot?

Before attempting to answer this question we need to set some limits to our subject. At the outset, we must recognise a difference between remotely-controlled systems and autonomous or semi-autonomous systems. In a remotely-controlled system, the man remains in control: examples include the French *VAB Top*(1) and *PackBot*.(2) The user of these never releases the control lever because, without the man in the loop, the system will simply stop. In contrast, a robot is autonomous or semi-autonomous. The *Roomba* vacuum cleaner, for example, falls into this category, as it is able to manage the level of dust in your home by itself. Of course military systems cannot realistically be compared with domestic appliances, since the specifications and tasks are hardly the same, but the comparison is made simply to underline yet again that we do not have any true robots in the Army. That said, it is not at all easy to a give a clear definition to the notion of robot.

One acceptable definition could be that a robot is an autonomous or semi-autonomous system that is able to act in the real world. It gathers information using its sensors, is capable of independent analysis and using its effectors can act on the world around it. The dictionary tells us that being autonomous means being able to administer to oneself, to be in control and free. It hardly needs saying that this definition of autonomy was created by humans for humans: robots have to be satisfied with a more restrictive definition. Before attacking the question of autonomy on the battlefield, it is important to remember that the real robotic revolution has not taken place in Afghanistan, but in factories and our own homes.

The civilian powerhouse

The military world has much to learn from the rapidly expanding use of robotics in civilian applications. The civilian market for robotics is driven by several trends, the main one being the cost of labour: our industries continually move their operations overseas in the search of less-qualified, but ever cheaper manpower. Such policies have benefited the consumer and the shareholder and, to some degree, the countries in which these companies set up their operations, all of which is to the detriment of our national workforce. The problem today is that these same 'expatriate' companies are finding it more and more difficult to lower their prices by keeping down the wage bill, for even in developing countries the talk is now of workers' rights and of demanding a living wage. To that should now be added the hike in transport costs that is encouraging some companies to adopt another model: complete automation of production. But who would prevent a robotised factory from setting up somewhere in France? Whilst many might wince at the idea of bras or running shoes being made by robots, rather than people, the taxes hoovered up by the state would probably convince the majority of our political leaders. Such robots, capable of working endlessly and never complaining, have already appeared in Japan and you will soon be seeing them somewhere near you. In the decade to come, we will start using products that have been made enti-

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(1) *VAB Top* is a forward armoured vehicle with a remotely-controlled mounting holding a 12.7mm machine gun.

(2) A small (18 kg), radio controlled tracked vehicle.

rely by machines. Happily, man will remain the master of the product design process for some time yet.

Some robots are already visible–those designed for the service sector, for example, a market projected to be worth some 100 billion dollars by 2020. Today, this market is represented by the *Roomba* vacuum cleaner mentioned before, but this is just the beginning. An ageing population is going to create a demand for specialised robots, already a strong trend in Japan. Isolation is a source of stress, and in South Korea and Japan, to alleviate this problem there is a desire to place a service, or servant, robot in every house to keep watch over the aged person at home using a number of sensors. It could vacuum the floors and help in food preparation; why not make it dispense certain types of care? Clearly, if the robot finds itself in some unknown situation, a human can always take over. Whilst the robots in use in our factories are simply articulated arms without any human aspect to them, those we would give to our parents and grandparents (and that might one day be given to us) will have to have a dose of humanity about them, and perhaps even resemble a human. They may even one day become our companions and friends: their presence in our homes would be intended to give us a sense of security, so why not a bit of human warmth, too?

This leads us to another major driver of the robot market–some would say the greatest driver–sex. The possibilities of linking robots with sex cannot be disguised. In South Korea, highly realistic dolls can be hired in specialist hotels, and there is a niche in the market for making these autonomous dolls more reactive. Today, we only have realistic dolls but in the future, in 20 or 30 years, say, it is perfectly possible to envisage robots whose basic function is to provide sexual satisfaction.(3) All these technologies coming from the civilian market will have an impact upon military fields of interest. We should not forget that in 20 or 30 years from now, the population will have become used to robots.

Delegation

Unlike the civilian market, which is always in search of something new, the military world is more prudent, and even sceptical regarding land-based robots. Today, delegation of human decision making to a machine is a taboo in the armed forces. Warfare remains the privilege of human beings because it is feared that any robotisation would dehumanise war even more than is already the case. The very idea of a land-based robot like *Terminator*, sweeping across the battlefield and mowing down defenceless humans, haunts us because there is only a tiny difference between the robots that would take our enemies' lives and those that turn

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(3) Patrick Lin, Keith Abney and George A. Bekey: *Robot Ethics: The Ethical and Social Implications of Robotics (Intelligent Robotics and Autonomous Agents series)*; The MIT Press, december 2011; 400 pages.

against us and take ours. This fear of *Terminator* lies deep within our Western subconscious and yet oddly it is not the case in Japan, and some other countries.

For all that, semi-autonomous systems already exist that are capable of taking life. The best known is the American *Phalanx* close-in protection system for warships.(4) In the air, a great number of missiles behave autonomously once fired, and on the ground, the *BONUS*(5) munitions fired by our 155 mm cannon could also be considered autonomous systems. They are able to detect the thermal signature of a manned vehicle and destroy it. So whilst a man fires the 155 mm round, for its terminal phase we have already delegated to a machine the decision to kill. Pandora's box has long been open, and there is little point in trying to close it again. Yes, we have already delegated something to a machine and yes, we are going to continue along the same road. Today's remotely-operated machines will gradually be automated–indeed, there is a real need for this. Take for example a *PackBot*, which is remotely controlled by its user: it locates an IED and starts to neutralise it, but at that very moment the adversary sets upon the *PackBot*-controlling team. The latter has to withdraw, but the time needed to make the robot safe exposes the team to enemy fire. Ideally, the operator should be able to press a button to allow the robot to act independently and return to a predetermined assembly point. Today's remotely-operated machines will only be really effective when one day they are given some autonomy. Tomorrow's transporter robot will be able to decide for itself on which side it should avoid an obstacle.

Missions

If we acknowledge that delegation of certain missions to machines is already the reality in some specialised military fields, what could we do for ground combat in particular? To simplify the debate, let's focus initially on the reflex actions of the soldier.(6) These actions are assimilated by infantrymen during their training, the repetitive nature of which programs them to react in a predictable and instinctive manner.(7) There are 11 of these actions: they will be very difficult, if not impossible, for a robot to accomplish in the coming decades. Only a robot with a high level of mobility and artificial intelligence (like *Terminator*, perhaps?) would be able to replace man, and that remains firmly in the realm of science fiction. But if it is not able to replace a man within a platoon or any other group, it could at least make some missions easier to accomplish. A robot integrated into a mobile combat group could, for example, survey a perimeter or reconnoitre a line of

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(4) *Phalanx* is an anti ship missile defence system with a high firing-rate of 3,000 to 4,500 20mm rounds per minute. The system has already killed humans in error.

(5) *BONUS* (*Bofors Nutating Shell*) known in French as ACED (Anti-char à effet dirigé).

(6) The reflex actions are: to protect oneself, advance, keep contact within the troop, appreciate distance, observe and note, designate a target, conceal oneself, orientate oneself, communicate, observe and fire, throw a grenade.

(7) Lieutenant-colonel (USA) Grossmanen: *On Killing: The Psychology and Psysiology of Deadly Conflict in War and in Peace* (3rd edition); Warrior Science Publications, october 2008; 403 pages.

advance.(8) The Americans have already reached this stage and have used some of their remotely-operated systems for reconnaissance missions. *MARCbot*, which was designed for vehicle inspection, has been used in a far more offensive manner: they attached a *Claymore*(9) anti-personnel mine to one of the Bots, then once the insurgents had been found, the operator activated the mine, which destroyed both the target and the *MARCbot*.(10) Now, the *MARCbot* is remotely controlled, but could the same thing be done with an autonomous machine? How can elementary orders relating to movement, direction, place to reach, itinerary, surveillance sector and so on be transmitted to a machine? A soldier will instinctively understand these orders, but not a machine–for now, at least. Should the commander have to master two procedures, one for the men and another for the machines?

Current technological limits

Robots have a role to play on the battlefield, but what will they be capable of? On paper, robots are better than men: they can be stronger and faster, they do not get tired, their 'vision' covers many spectra and they are devoid of emotion. In reality, however, these machines are very limited and will remain so for some time. To understand their limits we have to analyse the system through their basic functional blocks: carriage, energy, sensors, supervision system (in effect, the central computer) and effectors.(11)

Carriage, here, refers to the physical contact between the system and its environment–for example, between the wheels or tracks and the ground. We have already seen that civil robots will soon be invading our homes, but there is nevertheless a fundamental difference between the environments of civil and military robots. Whilst civilian robots will operate in familiar territory, the factory, the home and the street, the military robot will have constantly to adapt to the terrain. The importance to the Army of the terrain poses a real challenge to any engineer. In contrast to the drone, which operates in an allocated air corridor and without obstacles, a land system is constantly confronted by a variety of obstacles.

The second problem is energy. The energy produced has not only to propel the robot but also to supply its sensors, computers and effectors. So that it can form part of a combat group, the robot has to be silent, which excludes any form of internal combustion engine. On the other hand, electric propulsion is quieter but has limited endurance.

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(8) As a reminder, the missions of a combat group are: defend a point, reconnoitre, cover, reconnoitre a point, support, survey, seize, break contact.

(9) *Claymore M18A1* is a directional anti-personnel mine, capable of projecting 700 steel balls over 50 metres.

(10) P.W. Singer: *Wired for War: The Robotics Revolution and Conflict in the 21st Century*; Penguin, december 2009; 512 pages.

(11) A functional block is a sub-set of a system that permits the conduct of one or more functions.

We are wrong to think that a machine will be superior to man in the way it perceives its environment through its sensors. Man cannot see into the infra-red end of the spectrum but he can analyse what he does see in relation to his past experience, whereas a machine has to examine every image pixel by pixel. Many companies are working on this problem because the security industry is looking for an automatic analysis system for its surveillance cameras. For the moment, however, man remains unbeatable.

The principal difficulty lies in the calculator, or brain, of the robot; indeed, it is the Achilles heel of the system. For the moment, the ability to 'learn' is very limited and any notion of useful artificial intelligence is unlikely to see the light of day for decades yet. The robot's brain has constantly to merge and process the outputs of its sensors then adapt to its environment. It is only when all that is perfectly mastered that the robot will be able to use its effectors independently.

To all of this must be added another related difficulty: we, fallible humans, claim to be able to create an infallible system–the robot. Yet the algorithm that will operate the infallible machine is designed by fallible man, and the more complex the program, the greater the chance of error somewhere.

There are many technical difficulties to be overcome but we can have confidence in researchers and engineers to find solutions. One day in the not-so-distant future robots will be truly autonomous and will have the ability to administer to themselves; they will be stronger and more intelligent than us. Will they then wage our wars for us, or will we prevent them from doing so? For decades yet, the artificial intelligence needed for a robot to reason will remain in the realm of science fiction. In the foreseeable future, robots will not be entirely autonomous because it will be technically impossible for them to be so. Man will remain in or on the surveillance and monitoring loop, since robots with man out of the loop (in other words, totally autonomous) will not be technically possible. For all that, it is not too early to start asking questions about their legality in relation to *jus in bello* (Justice in war).

Ethical and responsibility issues

Let us now turn to ethical aspects of the subject. What bothers humans most about robots is the moral aspect of their use. Can we trust a machine to make a moral and just decision? But think–that question could be posed in another way: can we trust a human to make a moral and just decision under pressure in time of war? Take the example of the American sniper, Staff Sergeant James Gilliland, who took the decision to kill a child of eight because it was in the process of indicating the position of American soldiers to Iraqi insurgents.(12) His decision was entirely

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(12) Hans Halberstadt: *Triger Men: Shadow Team, Spider-Man, the Magnificent Bastards, and the American Combat Sniper*; St. Martin's Press, march 2008; p.101.

within the rules of engagement in force at the time, but was it moral and just? The answer is far from simple and depends on the pint of view taken. Now, imagine that it was an autonomous machine that had pulled the trigger: that changes everything. The Staff Sergeant in question has to live with the responsibility that he took the life of a child in difficult circumstances, whereas a machine cannot be considered responsible, cannot feel responsible for its actions and cannot be punished for them.(13) Responsibility then lies with the person who gave the mission to the robot and with he who programmed the rules of engagement into it.

A robot, however sophisticated, remains a machine, yet there are many examples of soldiers who become emotionally attached to their remotely-controlled systems. In Iraq, they gave them names and were photographed with them. Some even spent their free time fishing with them on the banks of the Tigris.(14) Some even went as far as to award their machines the title of bomb disposal expert and promoted them to soldier, first class. Humans tend to anthropomorphise inanimate objects, and this will be true for the robots of the future. If proof were needed of an extreme case of the attachment of a team to its remotely-controlled bomb disposal system, a soldier is known to have run 50 metres under enemy fire in order to rescue his 'wounded' system.(15) This anthropomorphism goes further still: a mine clearance robot was being tested. Its particular characteristic was to detonate the mines by stepping on them. At each explosion it lost one of its feet but nevertheless continued until it was on its last leg, so to speak. Unable to stand the 'suffering' of the machine, the supervising colonel stopped the tests.(16) He was simply attributing human qualities to the machine.

The ethical field is very broad, and covers the use of robots in war and their impact on our reticence to make war or not. More importantly, it takes into account our interaction with these machines.

Instead of a conclusion

Robots could be seen as simple replacements for humans on 3D tasks (Dirty, Dangerous & Dull), but they could also replace humans on high value-added tasks such as surgery. Moreover, robots can go where man cannot; they can be stronger, faster and more intelligent (in terms of computing capacity). But can they be truly autonomous? The answer is that they will be highly autonomous in a stable environment, which means in exclusively civilian applications. That excludes the battlefield (almost by definition, unstable), and therefore military applications.

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(13) Patrick Lin, Keith Abney et George A. Bekey: *Robot Ethics*; *op. cit.*

(14) Joel Garreau: *Bots in the Ground*, Washington Post; may 6th 2007 (www.washingtonpost.com/wp-dyn/content/article/2007/05/05/AR2007050501009.html).

(15) P.W. Singer: Wired for War; *op. cit.* p. 339.

(16) P.W. Singer: Wired for War; *Ibid.*, p. 340.

That does not mean that the robot has no place in the French Army. On the contrary! It will be able to take on many roles and evolve as technology evolves. The first uses could be in the field of logistics, to free manpower to perform other tasks, and in perimeter surveillance. Once everyone is accustomed to the use of robots in this first stage, semi-autonomous ones could be integrated into combat units. Tests carried out in the United States have shown that an autonomous robot is more useful than a remotely-controlled system. An autonomous robot will be more easily accepted because it does not add to a unit's overall workload.(17) Such robots cannot see any difference between a combatant and a non-combatant but will have the ability to scout out zones on behalf of human beings. Further into the future it is conceivable that armed robots will be used in killboxes–zones designated by the user within which everything is considered hostile. This is a tactic already in use in the aviation world but is an approach which raises alarm. We nevertheless have to consider it because other countries are already doing so. How long will it be before other countries start using autonomous battlefield robots?

Technology changes man, and some technologies lead to the complete transformation of our societies: the railway, the motor car and the computer, to name but three, have done just that. And yet nobody can predict with certainty the manner in which a given technology might transform society. One thing is clear: robots will transform us. It will not be a revolution, but a slow evolution, which will take place in our homes and on battlefields. France cannot afford to turn its back on this evolution.

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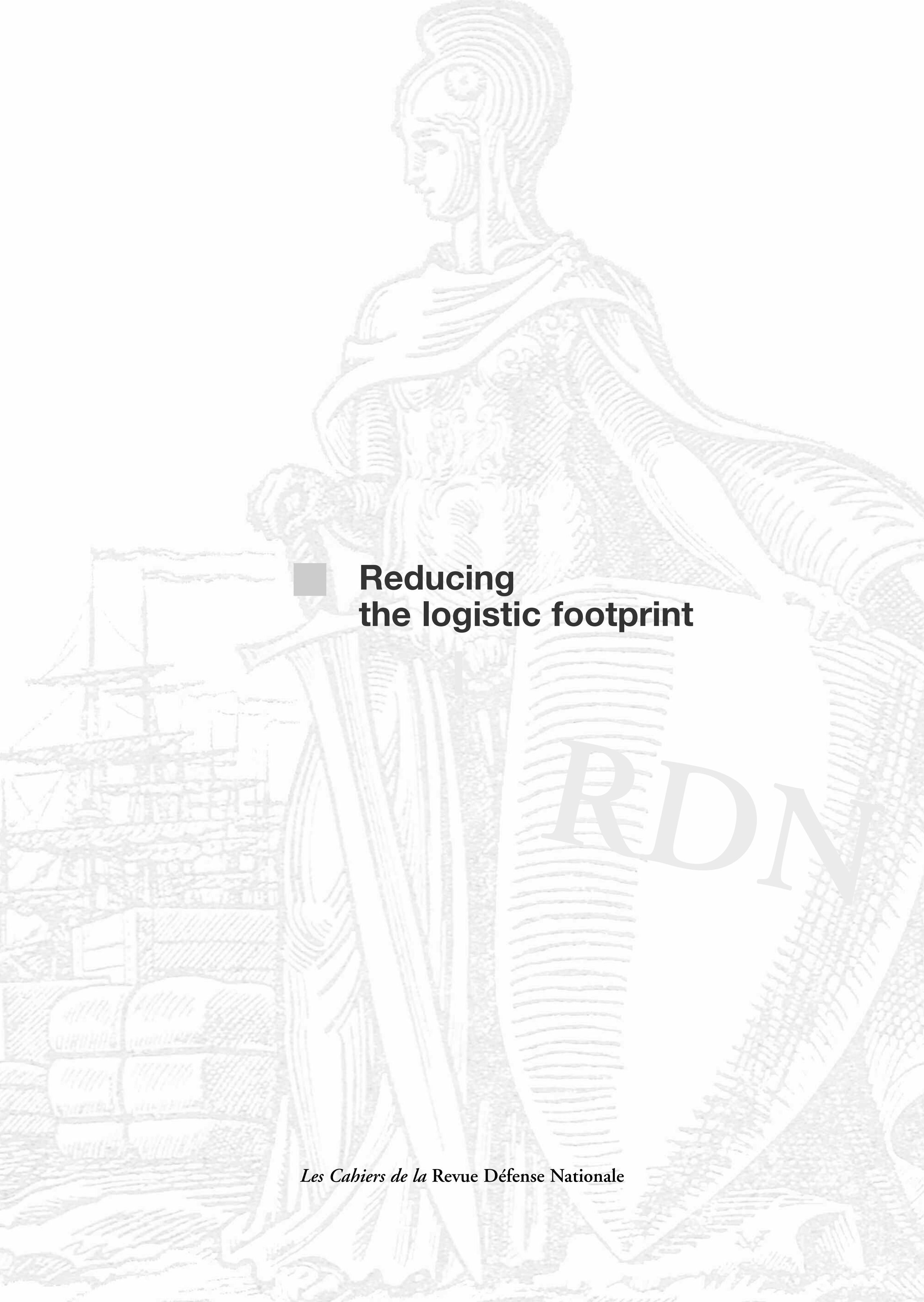
(17) Ronald Arkin: *Governing Lethal Behavior in Autonomous Robots*; Chapman and Hall/CRC, mai 2009; 256 pages.



Reducing the logistic footprint

Les Cahiers de la Revue Défense Nationale

Defence-industrial Partnerships for Logistic and In-Service Support

Jean-Paul Lafitte

Executive Vice President of the DAHER group and President and CEO of DAHER Industry and Defence

To enable the French defence organisation to concentrate on its primary tasks it may enter into partnerships with the private sector to provide some of its support. While some expertise must be retained in-house, especially that specific to the execution of operational tasking, the Defence Department can and should take advantage of a wide range of benefits offered by the private sector.

The armed forces are tasked by the government with carrying out certain duties on behalf of the nation, and recent curbs to their funding and equipment have made it all the more necessary to resort to partnerships with private industry. These partnerships are strategic in nature, and alliances must therefore be negotiated with industrial groups that can offer long-term reliable and stable services across all fields, be they technical or financial. Day-to-day support activities have already been the subject of a wide range of out-sourcing contracts, but much remains to be done in logistic support in general and in-service support in particular.

Firstly we need to consider the type of associate we seek. Naturally the major industrial equipment suppliers are best placed, as they are already involved in the in-service support of their own products, as well as their logistic support, either directly or via appropriate partners. The allocation of tasks during overseas or deployed operations remains to be clarified; there is as yet no clear definition of the level of direct involvement of private companies on the battlefield and some tasks must remain the responsibility of military maintenance personnel.

There are three logistics fields where the development of such partnerships appears to have much to offer. These fields are directly impacted by this initiative and merit a specific approach: national and cross-border transport, logistic supply and in-service equipment support.

National and Cross-Border Transport Logistics

The armed forces can call upon a wide range of transportation specialists that can provide all necessary services in mainland France, to troops stationed overseas or in support of the operational deployment of combat units. Only transport to front line units within operational theatres is excluded from this category.

How do we achieve this?

Transport resources over which the armed forces retain full control must meet their operational needs. When these resources are not being used, they may of course contribute to meeting peacetime logistic requirements, provided equipment service life is not compromised. Routine operation of such resources contributes only in part to the operational training of those personnel tasked with operating them. Such personnel must participate in operational training activities with the relevant equipment.

There is therefore a significant opportunity to negotiate partnerships with professional transport operators to complement the resources available through multi-national military cooperation agreements. This partnership, usually the subject of framework agreements, may take several forms: contracts for a specific charter of any type (maritime, air, rail or road), contracts for all transport operations within an operational theatre, multi-year contracts for continuing transport services and long term contracts ensuring availability of transportation resources, if necessary within a public-private partnership arrangement.

Added value from private transport operators

Cost-benefit analysis shows that using private providers offers two substantial sources of savings: a reduction in major un-productive capital investment through the use of resources provided by the private sector, which means expenditure restricted to variable costs over a limited period rather that the annual fixed costs generated by resources that are not used full time; and above all the use of personnel mobilised for specific tasks that are not strictly operational.

The ministry of defence thus benefits from resources that already exist on the civilian market and are often very modern, capable and maintained to international standards. Such solutions, when implemented by professional transport organisations, offer the military fully developed skill sets, especially where sensitive, abnormal or substantial transport tasks are concerned. These international transport tasks include transit operations such as customs clearance and regulatory formalities that demand specific expertise, ranging from a simple border crossing to more complex procedures for war material export authorisation.

In addition, with their simulation tools for the modelling and optimisation of traffic flow rates, private transport companies can offer innovative and reactive solutions to address urgent situations, including insertions into difficult theatres that they have often already visited. This type of contractorisation enables the armed forces to take advantage of the operational flexibility enjoyed by private companies, whilst complying with public contract legislation.

These global contracts, aimed at achieving capacity objectives expressed in terms of both performance and time scale, guarantee a high level of reactivity combined with a speed of execution that ensures satisfaction of the operational requirement. They are therefore perfectly adapted to expeditionary operations and involve not only the initial deployment, but also re-supply, unit replacement or redeployment tasks. Most transport tasks associated with expeditionary operations over the last twenty years have involved a significant contribution from private operators. Recently, for the *EUFOR Chad* deployment and subsequent withdrawal, the Libyan route was successfully and speedily reactivated, following diplomatic developments in the region.

Logistic Supply

Any permanent or temporary basing of military forces, whether in mainland France, the overseas territories or on expeditionary operations, requires an organisation to ensure the provision of all necessary supplies. As the armed forces need increasingly to concentrate their efforts on the preparation and execution of operational tasks, they look to outsourcing to fulfil the logistic function. This function covers all supply and re-supply tasks needed for the day-to-day running of the armed forces and their support in operational theatres, including all manner of consumable items and spare parts.

How do we achieve this?

Defence organisations must secure the support of associates that are capable of replacing the armed forces in logistic supply/support operations by sharing proven capabilities in both the military or other relevant sectors such as aerospace, the motor industry and supermarkets to name just a few. Associates must be recognised specialists in the various fields that the military wishes to delegate. They must be able to ensure that they maintain an equivalent or higher level of professionalism in the exercise of functions that are fundamental to the success of operations despite not being a core role of the armed forces.

To optimise efficiency, defence departments must be able to expand the boundaries of delegated roles to include such varied aspects as the determination of stock levels related both to historic values and stated requirements, the purchasing of products from suppliers, order monitoring through to product delivery, technical inspection on receipt, depot storage, preparation for despatch to meet requirements and distribution to users at unit level.

Departments within the defence ministry may adjust the volume of subcontracting to match requirements and the type of services needed. For certain categories of logistic supply outsourcing, defence organisations can achieve substantial savings by tapping into the capacity of the private sector to exploit resources and investments already available on the market, especially logistics facilities. In this way they can take advantage of variations in costs calculated as a function of the services provided and the level of achievement. Such a solution enables the optimisation of outgoings that could otherwise become prohibitive if retained in-house with low or erratic levels of activity. Defence is also obliged to seek out reliable associates that can provide cast-iron guarantees in respect of mission completion, and that have the necessary financial resources to meet the various restrictions imposed by the public contracts code.

Added value from private logistic associates

Associates (contractors) whose primary specialisation is logistics have their own technical support capabilities enabling them to operate specific information systems and to adapt them to the particular requirements of a defence customer. Such tools must enable service staff to obtain the information they need and guarantee management continuity and the monitoring of traffic flow through to operational theatres. Further added value arises from the ability to exploit flow-modelling software, which allows operators to introduce innovative solutions to optimise the overall cost of the logistic function. This might involve the introduction of new structures, or adaptation to changes in these structures.

Similarly, defence departments can also benefit directly from the many advantages that arise from the expertise and resources available to private companies, including use of existing logistics facilities with consequent scale effects and the sharing of platforms, consolidation of re-supply traffic flow grouped within a single centralised logistic system and optimisation of stock levels through better understanding of past consumption levels and rates, forecasting needs and shipping delays. This type of service provision has already been extensively trialled by logistics operators in France and other countries on behalf of a wide range of companies from various European industrial sectors, as well as for defence suppliers. Such companies dedicate all or part of the traffic along their supply chain for equipment logistics (which includes services for supplying production lines), for operational logistics (which includes ensuring availability of equipment and products to users), and for customer support, including spares management and the equipment cycle.

The ORRMA contract (which relates to optimisation of the re-supply of consumable aeronautical spares), that outsources consumable spares supply for SIMMAD (the joint service structure for the in-service support of defence aeronautical equipment), is a good example of this type of service. Its aim is to combine on a single platform all spares for the armed forces' aircraft fleets. The twin aims are to increase aircraft availability and reduce the capital sums tied up in spares stocks.

Equipment Logistics: In-Service Support

Regardless of the use to which equipment is put, as currently defined in the French Army's Fleet Operation and Management Plan and in other forces' support concepts, the aim is to guarantee the highest possible availability rate for equipment deployed on operations, while optimising in-service support within mainland France. While support in the field remains primarily the responsibility of the armed services themselves, partnerships with industry have become the most efficient means of achieving this. Within a framework defined by a contracting authority that must remain a government (defence ministry) responsibility, there is a wide range of services accessible to industry that so far has not been fully investigated.

How do we achieve this?

The contractorisation of in-service support involves the negotiation of broader contracts that may relate to specific items of equipment, under the control of their manufacturer, or to a major equipment supplier with a view to federating the various agencies involved in the maintenance of materiel and weapon systems.

The first solution is appropriate where there is **an availability commitment**. This type of contract assigns responsibility to a single prime contractor and centralises risks while relieving the contracting authority of the management of the risks associated with cross contracts. This leads inevitably to a reduction in the number of contractual contact points. On the other hand this risk management by a single prime contractor may increase costs. Under this solution care needs to be taken to retain as much competition as possible, reduce scale effects on transverse technologies and limit the ability of the contracting authority to oversee the sub-contracted logistic service providers (LSP).

The second solution is better adapted to **a capability commitment**. It presumes that certain contractual management activities are the responsibility of the contracting authority and this naturally reduces the amount of analytical system cost analysis, yet at the same time increases the risk of ambiguous or omitted areas arising from the matrix-based organisation. On the other hand, this solution would appear to offer a scale effect that promises rationalisation of the support structure, limits costs associated with sub-contracting, favours feedback and enables improvements to industrial policy based on growth and greater competition while improving the monitoring of sub-contractors.

Regardless of the solution adopted, an LSP who has been awarded an in-service support contract must take due account of the scale of the logistics exercise to be implemented. He will therefore either develop this function within his own organisation, or employ the services of a professional able to guarantee overall supply chain management and the implementation and monitoring of the flow of supplies, as well as coordination or provision of certain maintenance services carried out by him or assigned to sub-contractors.

This assumes the involvement of the LSP from the earliest phase, at the call-for-tender stage when groups are being formed. This will avoid limiting the scope of the service to be provided by the LSP as a result of restrictions in the public contracts code and in particular will enable make best use to be made of his expertise by influencing the content of the solution to be proposed; this will help to ensure coherence and cost optimisation. This coherence must take account of all relationships between companies and government LSP structures; the latter must be involved, especially in support of of external operations. It must also cover not only the physical movement of supplies, but also of information, which assumes that the LSP is in a position to offer appropriate specialist software or modules that are compatible with Defence and industry information systems.

The LSP helps to improve the cost-effectiveness of the in-service support system by contributing to investments, productivity improvements, task sharing optimisation, diversification of solutions and overall cost analysis. He contributes to the delegated contracting authority in his role as performance manager.

Added value from private LSPs

The main advantage offered by private LSPs in respect of in-service support lies in their ability to commit to an availability level that is remunerated as a function of the performance achieved. This guaranteed contracted target has real advantages for the armed forces. Continuity of appropriate support depends on a level of contractual flexibility that matches the need for flexibility that is inherent in operational sustainability. If the public contracts code is rigorously applied during the initial contract negotiation process, the LSP will then have a high degree of flexibility in developing his support structure, and this means that he will achieve the necessary reactivity.

Private LSPs have a greater ability to mobilise the technical expertise required to meet both routine daily requirements and the needs of operations but this will become increasingly difficult to achieve in a military environment where the safety of their personnel must be taken into account. This added value is very evident if one remains within the fields of day-to-day support or training; this is epitomised by the feedback following three years of experience from the out-sourcing contract based on hourly flying rates, aircraft availability and other resources needed for French Air Force pilot training at Cognac.

Future Prospects

The Defence organisation has completed its transition to a professional army and has now to address the demands imposed by the reorganisation of its support functions; the sharing of logistic and support tasks with the private sector should now be redefined. Some of our European partners have already developed some highly innovative support policies, along very different lines; these include solutions adopted by Germany and the United Kingdom. Lessons must be learned from this experience if we are to identify solutions that are appropriate for France's specific peculiarities, such as the public contracts code, and this in a context marked by intensive operations and re-organisations resulting from the security situation, the current economic crisis and budgetary stringency, and the demands of the Military Programme Law and the General Review of Public Policies.

The outcome of this should include the general introduction of partnerships with a view to assigning the majority of support tasks to private industry while maintaining firm state control as contracting authority, the creation of groupings of businesses combining financiers, the manufacturing industry and service providers. It should also be a driver of developing partnerships between the Ministry of Defence and the private sector, based on mutual confidence engendered by a high degree of transparency concerning targets to be achieved, procedures employed, organisations adopted and the resultant cost savings.

Numerous industrial groupings and LSPs are ready to join with the Defence Department in taking this matter forward.

The Logistic Footprint: Control Through Visibility

Thierry Veisemburger

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In recent years we have seen a fundamental change in the environments in which our armed forces are committed. We once had the notion of mass engagement against a known enemy within the framework of a defined coalition, whereas today we are involved in limited commitments of very varied forms against a changing and ill-defined adversary. A framework that is both multinational and joint has become the operational norm. Mutual logistic support is replacing single-source or single-nation supply chains, and is highlighting the problem of interoperability and the need to negotiate and build a logistic system for each operational event. Logistic capacity is becoming a real political and strategic challenge.

At the same time, the logistic system is all too often seen as a constraint, a consumer of human, technical, financial and geographical resources, an organisation with too great a footprint and, not least, a vulnerability. Given this, any proposal to reduce the logistic footprint always seems an attractive option but it is a dangerous exercise and we should beware of going for the wrong target. What is needed is not to seek to reduce logistics in general, but to look for a support system that is appropriate to the task and mobile (with reduced inertia), that will become a real factor on effectiveness of an operation. I feel it better to speak of controlling the logistic footprint than of reducing it. It is as much the developments in logistics as those in technology that are leading to the optimisation of new possibilities and a revolution in manoeuvre. Today, control of logistics within an operation is clearly an element of power.

Three key factors, a lever for control

The armed forces are currently undergoing transformation based on optimisation of their operational capabilities. That said, the conditions under which forces are now deployed, which are in the main expeditionary, make logistic performance more than ever a condition of effectiveness of the overall operation. The concept of operational support relies on interoperability and doctrinal documentation, and is set clearly within a framework of multinational operations, which are now the reference for French commitments. Support of forces on an operation goes from the moment of their departure up to their withdrawal, and concerns all the support measures and actions needed to allow a deployed force to establish its position and live throughout the term of the deployment, and at the same time to act whilst maintaining combat effectiveness. This being so, when looking at logistic footprint three key factors have to be taken into consideration:

- The logistic weight of the force: different factors influence the logistic weight of a force. These include principally its equipment, its area of action and, of course, the type of action.

- Mobility: whether strategic or tactical, mobility relies on some system of management of transport and transit.

- Support of the force: force support is characterised by the requirement to satisfy as closely as possible the needs of each operation, drawing upon anticipation, permanent adaptation to circumstances and optimisation of resource.

It can be seen that these factors are interdependent. For example, impaired mobility will very often lead to a significant increase in stockholdings, and as a result add to the logistic weight of the force. The immediately obvious consequence of this is that the logistic footprint is dependent upon a sort of alchemy between these three factors. On the other hand, the notion of resource remains a constant among them:

- The logistic weight of the force is the entire collection of resources of all types and natures.

- The aim of mobility is to transport the resources from place to place in a given time.

- Supporting the force consumes resources.

This observation leads us to consider control of resource as the principal lever of control of the logistic footprint. It does not, however, call into question the other levers that directly or indirectly influence the logistic footprint, such as energy management (which includes the consumption of equipment and standardisation), waste management, equipment maintenance, means of transport and the productivity of the support facilities.

Controlling resource

The resource is the fundamental element upon which action has to be taken. It has a life cycle, which must be followed and managed. This life cycle can be divided into five processes:

- Creation: why and how the resource was created;

- Tracking: the position (geographical and status) of the resource;
- Management: use of the resource within the supply chain (including storage, management of time-limited (or perishable) stock and distribution);
- Consumption: the end use of the resource (consumption, re-use, life);
- End of life: how and why the resource's life cycle ends.

It is necessary to have clear visibility of the resource throughout the supply chain. Such visibility is gained by knowledge of upstream stocks, of the resource being handled and of downstream stocks.

Visibility of the resource

In French doctrine publications, 'visibility of the resource' is defined as 'corresponding to the ability to know the identity, position, quantity and state of resources at a point or in a part of the supply chain.'

If they have permanent knowledge of losses, damage and consumption of the resource on one hand, and its position, quality and availability on the other, logisticians can be in a position to drive the logistic chain by positioning support facilities and stocks to guarantee maximum effectiveness. The increasing cost of weapons and their maintenance means that not only are means required to ensure their maintenance in fighting condition, but also (and above all) real visibility of the situation of the deployed assets and the technical resources needed to maintain operational capability. This visibility is the sole guarantor of the efficiency of support services. Besides that, the increasing cost of resources in a time of budgetary restriction is forcing a rethink of the size of stockholdings: the cry today is 'just enough'. In order to gain a true measure of the adequacy of stock levels against operational needs and imperatives, tools and means of measurement and evaluation are needed. The efficiency of support services, together with 'just enough' stock should in the long term lead to significant cost reductions. Visibility of resources offers a real potential for reduction of stock holdings.

The capabilities outlined above can only be acquired by setting in place systems of tracking and management of the resource. Yet visibility cannot be achieved by tracking alone. It is not a question of focusing on any one particular observation, but of being able to know, anticipate and predict in order to act on all the information gained in a proportional, suitable and coherent manner. Acquiring this capability therefore lies at the very heart of the subject, and the information then obtained must help those responsible at the different levels in the supply chain to take the appropriate decisions which lead to:

- Reduction in reaction and delivery times;

- Reduction in cost;
- Optimisation of stocks and transport.

These capabilities contribute directly to control of the logistic footprint. To achieve this latter objective, information also has to be under control: this means making available the right person and the right information, at the right time, in the right format–and in all circumstances.

Control of information

The need could be summed up as control of information about resources. The right tools are needed to ensure total visibility of the resource in order to have a real capability for assisting decision-making for the logistics branches.

Numerous in-theatre logistics information and communication systems give us the capacity to hold vast quantities of information. Whilst all this information aids the assurance of tracking and conduct of operations, for the logisticians it also leads to partitioning of different aspects of the supply chain. It is essential that the logistic function has the capability to assemble relevant information in order to provide a wider view of the logistic situation.

Forces have to fight as much for information as because of it. Information-supported operations should allow significant advances in a number of areas, notably logistics. Information support should lead to the fast and easy exchange of information between all players, whatever their geographical position or their functional chain of command. An overall management system for the logistic chain permits recognition of problems, or potential problems, in good time. It is therefore possible to create an overall logistic picture which puts logisticians in a position to evaluate in advance the logistic consequences of actions, to apply corrective measures as required and to define ways of implementation that will guarantee the greatest effectiveness of logistic assets. This means improving the service in cost terms, and not just the service alone.

The operational context in which tracking and management of the resource are conducted demonstrates the vital necessity to have reliable, pertinent and coherent information about resources in order to respond to new operational logistic challenges against a background of ever tighter financial constraints. Such information changes and is exchanged in a complex, developing and sometimes unstable environment.

In the supply chain, this need for information concerns many players at different working levels (strategic, operational and tactical), different levels in the chain of command (from the staff officer working in concepts to the worker bee who delivers the goods) and working for different organisations, be they military (national or allied) or civilian (administrators or service providers). Control of information must provide all of these people with:

- Assistance in the design, planning and conduct of the logistic aspects of operations;
- Assistance to the coordination of the various players through appropriate and personalised information;
- The capability to coordinate, control and conduct supply lines and replenishments;
- The capability to know the availability and quality of resources.

Once again, these capabilities contribute directly to control of the logistic footprint. To achieve such performance, information has to be considered as a kind of raw material, to be rigorously managed just like any other resource. Thereafter, to have full understanding of the deeper implications of this control of information, one has to understand the characteristics of the supply chain itself.

The supply chain

The supply chain can be considered the backbone of the logistic system. The life cycle of a resource is tracked throughout this chain. Indeed, a resource only exists in order to gain some capability, which will in turn be assured by the supply network. Information about a resource has to be available throughout its entire life cycle in the supply chain. The main characteristics of the supply chain are its:

- Joint force, multinational and civil-military character;
- Information chain, adapted to the circumstances of its use (France only, UE, NATO, UN, Coalition and so on) and to the national need;
- Parallel nature with regard to the chain of command–it is subordinate to the command chain but is managed independently;
- Continuity from suppliers or infrastructure depots in the homeland to the lowest level of force support;
- Permanent service for forces in the homeland, for those pre-positioned and for those deployed;
- Adaptability as a function of changes in mission/context or action of the force;
- Players, who could be national or international, military or civilian;

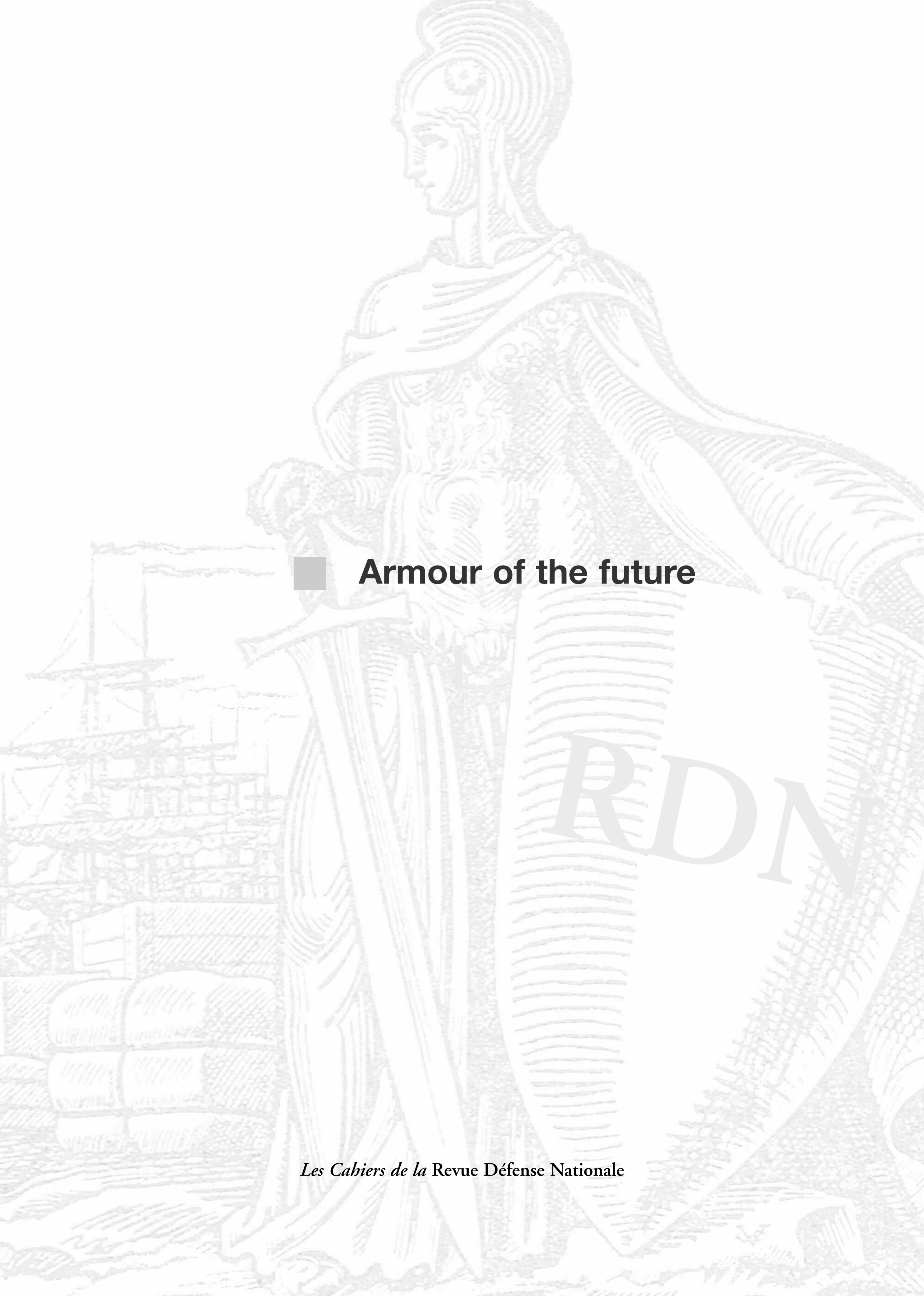
- Organisation, which is adapted to the type of support required (for example, that required by maintenance services differs greatly from that for MEDEVAC).

Correct support of forces relies on an information system that allows tracking and timely management of resources, and is characterised by the need to respond to operational needs as closely as possible, drawing upon anticipation, permanent adaptation to circumstances and optimisation of the resource in question. Yet logistic performance cannot be achieved without anticipation: planning time has to be found in advance of the operation–this is nothing other than the logistic version of the principle of freedom of action. Deployed forces need to have the capability for frequent and rapid changes of configuration so they can adapt to changing environments and threats, or even to complete changes of mission.

In conclusion, we can say that control of the logistic footprint is dependent upon control of resources. Such control affords the different players in the supply chain real help in decision-making so that they can optimise the logistic infrastructure in order to guarantee the success of the mission.

In short, having complete mastery over resources means:

- Having an overall, instant and predictable view of logistic capacity;
- Being able to control flows to maintain logistic capacity;
- Controlling transport, storage, distribution and handling costs;
- Controlling the use of perishable and critical resources, and thus their associated costs;
- Coordinating the action of the different players to ensure the right resource in the right place at the right time for the right customer;
- Estimating future developments and anticipating needs in order to shorten reaction times and avoid rupture of the supply chain.



Armour of the future

Les Cahiers de la Revue Défense Nationale

Avenues of Research for the *DGA* in Armoured Protection

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New methods of ballistic protection are high on the list of priorities for the *Direction Générale de l'Armement* (*DGA*) in its work on materials, which is an important factor in technological capabilities such as efficiency and protection of the soldier, optimization of armoured vehicles, innovative naval platforms and future aircraft platforms. Scientific research in the field of materials, chemistry and energy is directed at protection and perforation to respond to the military requirement for equipment (land sea and air transport) and personnel protection (which includes ballistic body armour, helmets and helicopter seats), and the civil need for the safety of goods and people (in civil aircraft and on the railways, such as frontal protection for high-speed trains, food transport and building protection—for example, nuclear power stations, official buildings, banks and commercially prominent buildings).

Solutions for protection against ballistic or explosive threats essentially seek dynamic mechanical performance, which boils down to behaviour under high-speed deformation, shock-wave propagation in materials, modes of damage and dynamic rupture and erosion under high pressure. Even though it is the material parameters which govern these properties, it is necessary to think in terms of protection solutions as a whole, rather than just of the material itself, since the effectiveness of the system will depend as much on the design of its components as on how they are manufactured. To be able to optimize a system of protection it is necessary to think in scales running from the microstructure of the material, through the macroscopic structure to the assembly of the various components which will make up the finished system in its working environment.

Protection is increasingly designed to provide improved performance for a system and the current tendency is to do this by combining protection with another function in a complementary fashion. The multi-functionality of equipment, in addition to the lightening of structures, is a priority area of scientific research. It is not possible to speak of a material without associating it with the procedures used in its manufacture because it is always these which will, to a large extent, control the final properties obtained. Taking the notion of 'reparability' of armour into account at the design stage enables maintenance costs to be minimised when it is replaced. The choice of protective materials will also be made taking into account recyclability and the energy costs of fabrication.

In parallel with research into structural characteristics, scientific interest also focuses on the properties and behaviour of materials over the whole range of impact velocities to be encountered, from quasi-static levels of a few metres per second (m/s) typical of car crashes, bird strikes, gravel impacts etc. through high-speed deformations at the order of 1,000 m/s encountered in ballistic impacts to even higher speeds for threats such as hollow charges, hyper-velocity weapons or space debris. Behavioural modelling and trials, which are necessary for final validation and for calibrating models, provide validated mechanical behavioural laws. These can then be used to create representative simulations and reductions in the development costs of future protection solutions.

Some research priorities

It is only possible to propose and optimize ballistic protection by studying the threats and by continually adapting the protection in parallel with the threat likely to be encountered. This means conducting research into these two areas to understand the behaviour of the materials to be used. The behaviour observed is very closely linked to the manufacturing process because it is basically the microstructure of the material which governs the relationship between the structure and its material properties, and hence the performance of the system.

Threats

The threats will differ in nature and in the energy which they transmit to the target. We can distinguish between energy projectiles (bullets, shell splinters and penetrators) and directed energy ones (hollow charges and explosively-formed projectiles) as well as 'natural' projectiles (hailstones, birds and debris) which systems such as cars, trains, aircraft, missiles and satellites are likely to meet.

The increasing terrorist threat and asymmetric conflicts have seen the emergence of new threats such as home-made bombs and mines, combining blast effects with multi-material multi-form impact and termed improvised explosive devices (IED). Attack by IED is becoming a high-priority subject, and the next edition of NATO STANAG 4569 will include it. The level of protection of land vehicles has to take this new problem into account and will rely on new armour solutions for occupant protection.

Low-energy impacts such as those involving falling objects or blows to a pilot's helmet of a few metres per second, also require evaluation and the development of appropriate protection.

Military warheads

Kinetic energy projectiles apply the energy of the projectile to penetrate the target. At the moment of impact this kinetic energy, E, equals ½mv². Such projectiles rely on the mass (m) parameter in the equation. Each consists of a rod-like heavy-alloy penetrator, stabilized by spinning in flight, guided and propelled within the gun by a discarding sabot. The smaller the section of the projectile and the higher the ratio of the mass to the section, the greater is the impact pressure on the target. Work in this area is essentially on the microstructure of penetrators and hence on their manufacturing processes. For protection against these projectiles, research effort is concentrated on methods of absorbing the energy.

In the case of directed energy projectiles such as hollow charge types velocity becomes paramount. Hollow charges are developed to penetrate the armour of heavy vehicles. Such charges are made by arranging an explosive charge around a thin metal cone. The initiation of the explosive occurs behind the cavity thus formed which causes a focussing effect of the detonation gases. The shock wave, which typically travels at 8,000 m/s, projects the thin lining forward along the axis of the munition and the projected material forms a heavy slug, while the gases form a low-mass but very fast-moving jet. The target receives a jet of molten metal moving at several km/s whose penetrating effect is extremely powerful. To achieve high performance it is necessary to use lining materials of high density and ductility.

Research on kinetic energy projectiles

In the field of kinetic energy projectiles work is underway on new manufacturing methods such as spark plasma sintering (SPS) or microwave sintering, which allow the combining of different materials while controlling their microstructure and hence their properties. Each of these sintering technologies has advantages and disadvantages and all are worthy of investigation in the context of research into rupture technology.

SPS technology permits both the combination of powders of different natures by co-sintering and welding without a filler metal. This enables two large parts to be joined to obtain a component with continuous mechanical properties. The use of sub-micron or even nanometric powders enables the sintering operation to be carried out with a very short cycle time, which prevents the introduction of fragility due to grain growth. This technology allows the production of solid bi-phase metallic alloys while avoiding the formation of weakening intermetallic phases. One possible application of this is the development of penetrators in tungsten alloys, which could replace depleted uranium munitions.

Metallic glasses are new materials which are completely different from other metallic materials. Their deformation mode favours the penetration of homogeneous armour and they are therefore potential candidates for new generations of perforating munitions. They constitute a new type of material with a great potential for a number of applications thanks to:

- their unique mechanical properties: a high elastic limit, a high capacity for storing elastic energy and a low coefficient of friction;

- their combination of unique properties: mechanical behaviour and resistance to corrosion, their biocompatibility and their low density;

- the possibility of precision moulding them, thermo-plastic style, which is unusual for metallic alloys;

- their great capacity for modification, by means of control of the chemical composition and the formation of a composite. The glass becomes ductile by crystallization or the controlled substitution of different chemical elements, making the resulting alloy denser or lighter.

Ongoing work concerns the subtle variations of metallic glasses with high mechanical resistance and capable of plastic deformation while retaining good penetrating power. The orientation and control of the microstructure during manufacture enables the properties to be optimized, and this can be achieved by reinforcing the material using crystalline dispersants which promote the insertion and orientation of crystals to form composites.

It is also possible to work on the metallurgy of powders to develop new kinetic energy penetrators in the form of composites with a metallic glass matrix made by the SPS process containing a hard reinforcement such as tungsten. The particle size is tailored to obtain a percolation giving the desired properties. For the protection of light vehicles the development of reinforced metallic composites, for example nano-reinforced (by diamonds or something similar) aluminium could be a solution, but it would need to be validated and compared with existing solutions.

Research on hollow charges concerns materials such as copper, nickel and molybdenum for the fabrication of the conical liners. The metallurgy has a strong influence on performance; a high-purity copper with the finest microstructure possible promotes the elongation of the jet. It would be a good idea to explore this as far as possible by controlling the thermo-mechanical treatments applied during manufacture. Work is underway on the nano-structure of the surface treatment.

Protection

Work on the development of protection is centred on responding to a wide range of challenges related to the threats described above, and depends on the materials used. These different protection systems can be classified as a function of the materials and the scale of the challenges to be faced in terms of energy:

- opaque protection of vehicles (heavy, medium and light, as well as helicopters);
- transparent protection for vehicles in the visible and infra-red wavelengths (protection of optics, windows and episcopes) which must be totally multifunctional as regards transparency, robustness and so on;
- combatant protection (waistcoat, helmet, visor) especially in the context of the development of the future infantryman (Félin), where the weight of the protection is a determining factor;
- protection against low-energy impacts such as helmets for fighter pilots;
- protection of infrastructure.

Definition of protection

Because of the energies involved in an impact, the simple solution of interposing passive metallic protection is not always possible since that could lead to impractical thicknesses and therefore weight of armour. Several categories of armour solutions are recognized according to the threat level: passive armour (for example ceramic/steel composite armour), active armour and reactive armour. Non-explosive reactive armour (NxRA) works by the movement of a thin metal plate fitted behind an outer layer of armour. This increases the effective thickness of the armour and defeats a hollow charge jet. Reactive armour is made up of a sandwich structure containing a layer of explosive as the filler, which detonates under attack from the jet. The movement of the two outer plates of the sandwich in opposite directions destabilises the projectile or disrupts the jet depending on the type of attack.

For the largest kinetic energy projectiles such as the long rod penetrator, whose impact velocity can reach 1,800 m/s (Level IV of the *STANAG* is 911 m/s and Level V is 1,335 m/s), increasing the armour thickness is no longer feasible and the most effective solution is to break up the projectile using various materials. A hollow charge will penetrate a thickness of steel corresponding to ten times its diameter, so it is not possible to depend on the thickness of the armour to provide protection. Theory indicates that the depth of penetration increases linearly with the length of the jet and with the square root of its density. For this type of threat reactive armour is generally used.

For protection against blast weapons, for example thermobaric munitions, structural factors must be taken into account rather than the materials involved. For this application, research effort is based on structures aiming to deflect the blast rather than resist it head-on. The fragments involved, although small in mass, can have speeds of 4,000 m/s. In developing structures, the scientific work essentially concerns assembly technologies and welding techniques.

Vehicle armour

The basic principle of an armour system as far as the material is concerned is to combine a hard outer facing material, intended to break up projectiles, with a highly ductile lining material behind it to stop the fragments which are created. This combination of properties is currently incompatible in a single material and therefore requires an 'armour solution' employing for example a ceramic material applied to a steel or aluminium structure, or a ceramic embedded in a polymer matrix. To improve its performance a composite backing, or anti-spall lining, to stop splinters is frequently attached to the rear face to form an extra layer of armour. The value of this extra layer has been demonstrated on an aluminium structure to stop simulated projectiles of the 20FSP type (IEDs and splinters).

Research in this area is directed at hard materials such as ceramics for the outer face with more ductile metallic materials behind, and on new concepts resulting in materials with a gradation of properties. Also under study are the constituents of these elements as well as the processes for developing and combining them. Another avenue of research is looking into fibres, the method of weaving them into a textile and their integration and assembly into the armour solution, in particular for crew protection.

The assembly procedures of the different elements of the vehicle structure are also assuming great importance. Advanced welding techniques (by friction, laser, electron beams and plasma arc without filler material) and multi-material assembly techniques have a major influence on the behaviour of the structure. The optimization of the parts, taking advantage of new materials and assembly procedures, can mean a considerable weight saving, with a corresponding improvement in the vehicle's performance.

Hard materials: ceramics

Ceramics are known for their potential as an armour constituent. Their performance is linked to their low density compared with ductile materials, associated with excellent mechanical characteristics. However, their ballistic performances vary considerably, depending on their composition. But the performance of armour does not depend only on the characteristics of the ceramic used; its integration into the armour system is fundamental to the overall effectiveness of the protection offered.

In the field of opaque ceramics used for ballistic protection the materials of choice are sintered alumina, silicon carbide (SiC) and boron carbide (B_4C), the latter being densified by sintering under pressure, which currently makes it costly and little used in manufacture. The titanium compound TiB_2 in the form of a nanostructure is also a ceramic of interest that is being developed for protection. Composites of a metallic matrix reinforced by encapsulated ceramic also make it possible to lighten protection systems while retaining good ballistic properties. Other avenues of research are being explored with the aim of developing high-performance products capable of competing with the best ceramics used today to achieve higher protection levels. This work concerns alumino-silicates and boron carbide. The improvement of silicon carbide nevertheless remains a subject of great interest.

Products resulting from alumino-silicate mixtures possess the advantage of lower density (3.2 g/cm^3) than alumina products (3.8 to 4.0 g/cm^3) which are the reference materials forming a large part of the market in armour ceramics, while exhibiting promising dynamic properties in the area of mechanical behaviour in high-speed impacts.

Boron carbide is a material which combines low density (2.5 g/cm^3) with particularly high hardness (3,200 kg/mm^2) and a high melting point, which make it especially useful in the creation of protective systems. Research into this material is following two approaches, one on understanding the structure of the material and the mechanisms involved in the dissipation of impact energy, the other more theoretical work on the manufacturing, in order to reduce the costs of fabrication. B_4C with 20% carbon is processed fairly easily, making it a very common material for industrial cutting and grinding applications, similar to diamond or cubic boron nitride (BN). However, the use of this ceramic as an armour material remains problematic as it has poor resistance to shockwaves. Current efforts aim at studying the properties of the basic state of B_4C and other materials of similar composition (that is, those which have a carbon content of about 20% and presence of faults), in the free state and under pressure, in order to understand their behaviour.

On the second point, the technique called ‘reaction bounding’ developed by Israel is an interesting route to explore. These ‘low temperature and pressure’ processes enable materials based on SiC or SiC/B_4C to be developed at a lower cost.

The question of transparent armour also corresponds to an expressed requirement (vision panels for shields, visors for combatants or for vehicles). Transparent ceramics could replace the magnesium minerals currently used with much better ballistic resistance properties than other materials such as glass or sapphire but at a high cost and without a French producer, resulting in dependence on the United States. A solution could lie in their fabrication using SPS technology to reduce their cost.

Ductile materials

The integrity of structures is considered in parallel with, and for the same reasons as weight reduction during the design of defence systems: the improvement of protection weight for weight and/or the lightening of protection systems. Two main families of metallic materials are used in the armouring of vehicles: steels and aluminium alloys. Nano-reinforced light metals constitute a new avenue of research to meet this need, such as metallic glasses.

Work on protection materials is directed at:

- titanium alloys, whose properties promise both structural and armour applications (specific effectiveness 1.5 compared with steel) but the cost will have to be reduced. New very high-performance alloys could permit technological breakthroughs without requiring over-complex systems;

- absorbant composite materials (hollow balls or honeycomb core structures associated with ceramics) for anti-mine floor applications and in the context of protection against IEDs.

- materials with gradient properties. The aim is to find good combinations and to develop new technological solutions using the SPS process.

As with penetrators, SPS technology can be applied to the manufacture of armour components. The use of nanomaterials combined with SPS and/or microwave technology will permit the reduction of vehicle weights as well as the cost of ballistic protection. This technology also enables materials with a gradient of properties to be produced, nanostructured and formed in short fabrication cycles. It is a promising route to a combination of materials of widely varying properties, like the association of ceramics and metal to counter the fragility of the ceramic.

The innovative aspects of the solid metallic glasses described above also offer applications for protection. These materials, through their ability to combine low density, elasto-plastic behaviour and erosion mechanisms comparable to ceramics, could constitute solutions for armour systems. The new properties of metallic glasses compared with traditional metallic alloys, with their improved thermal stability and low density, also offer the prospect of innovative applications in the civil sphere, such as mechanisms (cars and other machines), leisure and aeronautics, thanks to their thermal stability.

Liners and textile materials

Textile materials, either flexible or in the form of fibrous reinforcements for composite materials have seen increasing use in many areas to lighten structures but also for protection. Composites with woven reinforcement are increasingly used in applications where good mechanical performance in situations involving impact, damage or fatigue is required. Existing armoured protection of the aluminium structure of land transport vehicles is reinforced by fibrous materials with high mechanical performance for IED challenges using splinters. The fibres used in the fabrication of armour are mainly glass fibre, aramid or polyethylene. However, new fibres, Vectran for example, are appearing on the market. This is leading scientists to study ways of improving the mechanical properties of textiles used in protective armour.

Bi-dimensional structures, particularly layered ones, are leading the market for woven composites. With their high fibre content, these materials offer high resistance to rupture and high rigidity. In the event of an impact, the structure of the material is challenged transversally to the layers of which it is composed. When the composite is challenged in another direction, de-lamination occurs, making the composite ineffective. De-lamination can occur at the interfaces between the fibres and the matrix, but also inside the matrix, or rupture may be initiated in the anisotropic layers of the stratified structure. In order to improve the protection performance, the use of a three-dimensional 'interlock chain' type of reinforcement can offer innovative solutions and permit the lightening of the overall armour system. Similarly, it is possible to conceive of fibres grafted transversally with nanoparticles to provide 3D reinforcement.

Compared with conventional fibres of glass, carbon or Kevlar, new technologies offer the prospect of fibres developed from carbon nanotubes (NTC). In the first place this requires reproducible methods of making these into thread and then weaving it into a textile in order to fabricate parts. The properties obtained from fibres made by using NTC in single or multiple layers will apparently be very different.

A distinction must be made between flexible protection (such as required for bullet-proof jackets, airtight bags and combatant protection) and rigid protection (armour for land vehicles, supplementary protection for body armour and so on).

Combatant protection

In the domain of combatant protection it is not feasible to make very thick armour, due to weight and bulk constraints. The current objective is the lightening of individual protection to the extent of 10% in weight over the next five years for the same protection and 20% in ten years. Flexible structures are required which can adapt to the morphology of the combatant. Other parameters to consider are multiple threats such as blast and splinters, an increase in the number of impacts that the protection is able to withstand, ergonomic improvements, a reduction in volume, the behind-armour effects on the human body and post-impact protection in relation to the spectrum of threats (anti-trauma).

As for work on anti-trauma, the orientation of material research is suffering from a lack of experimental data and methods of evaluation. The improvement in head protection (helmets) remains a very important objective and must be seen from an overall perspective of both ballistic protection and anti-trauma measures. Protection against a threat larger than the 9mm round, which is the current limit, remains a high priority. Materials of the rheothickening type, with the idea of a 'liquid armour' which hardens on impact, is a solution worth considering and which appears to have been developed in the United States and South Korea.

For the protection of systems against lower-energy shocks (such as a pilot's helmet), the protection concept will be based on the development of shock-absorbing materials by modifying the nature of the foams and resins which make up the various associated components. The development of foams and resins containing elastomers or nanostructured terpolymers will improve the effectiveness of the protection by dissipating the impact energy.

Protection of infrastructure

For infrastructures, the activities pursued mainly use concepts used in civil engineering (new concretes, construction and reinforcement technologies). However, particular effort is being expended on the characterizing of concretes and their behaviour under high-energy attack, such as by missiles.

As for other materials, the structures of aggregates, their arrangement in the binding matrix and the water content of the concrete are factors which must be modelled and understood. Isostatic compression tests and research into mechanical properties in extreme conditions, with dynamic challenges using Hopkinson bars, are conducted and provide modelling data and behaviour predictions.

Trials

The conventional method for defining the performance of a material and a protection solution remains the ballistic test. This approach is relatively economical for each material tested, but turns out to be expensive over the long term. It tells us nothing about the micro-mechanisms which characterize the response of the material and determine its resistance to penetration. In addition, the exploitation of trials is handicapped by the complexity and multiplicity of the mechanisms involved.

An alternative approach consists of using laboratory instruments to characterize the response of a material. This can involve detonation experiments, plate impacts, Hopkinson bar trials, experiments on fragmentation through impact on a section or drop weight trials, and will be associated with simulation and modelling. The trials aim at evaluating the performance of penetrators and their mechanical behaviour at the target.

Some specialized tools are involved such as the pulsed electric generator and the tri-axial compression press. For trials, use is made of the resources owned by universities and high-profile French colleges such as the *Polytechnique*, the advanced engineering systems college (ENTSA), the life sciences group ICA and others. In the development of launchers, contact is maintained with industrial companies such as Thiot, with a view to developing trials equipment capable of achieving impacts of 10,000 m/s to simulate impacts with orbiting satellites and to permit the definition and understanding of the physical laws involved. To improve the materials used in these launchers particular attention is paid to methods of hard chroming tubes using vapour deposition techniques (PVD and CVD) and also plasma deposition technology, which uses structured nano-powders to deposit coatings with very good properties, compatible with developments imposed by environmental regulations.

The design of a structure requires a precise knowledge of the challenges to be met; this typically means modelling of solid-to-solid impacts or the shockwaves following an explosion.

Digital simulation: modelling

The structural resistance of defence infrastructure systems depends on the knowledge and control of several factors: modelling of structures and different assembly techniques, a knowledge of the types of challenge and a good estimate of their characteristics (level and frequency), and the properties and behaviour of the materials.

The ability to model and simulate the behaviour of materials and structures enables the costs of development and qualification to be reduced by limiting the number of trials required to verify the accuracy of the theoretical calculations and their recalibration if necessary. Simulation can never be an end in itself, nor is it enough qualify a material or a system. Behavioural models are no more than simple representations of reality; trials can be reduced in number but will always remain indispensable. To address dynamic problems effectively, explicit codes are used from companies such as ANSYS for quasi-static situations or Livermore Software's LS-Dyna, but more open codes such as Abaqus are also used, allowing the introduction of specific behavioural laws, particularly for composites. The development of advanced digital methods is necessary to describe better the behaviour of multi-material structures and the technologies of combinations and structural assemblies employing welding, adhesives and the like.

Various rules governing damage, crack propagation, perforation and so on are integrated into the models developed. Modelling particularly concerns impact, the simulation of dynamic effects within the material and the understanding of these. For example, the digital simulation codes will include ceramic/metal combinations able to offer better ballistic behaviour than ceramics alone.

To deal with problems for which an Eulerian hydrodynamic code is unsuitable, a code with a particular application (eg *Radioss*) is necessary. This type of code is used in studies of personal and vehicle armour. For specific needs the *DGA* uses the Eulerian code *Ouranos* developed by the French research organization

CEA. It enables the kinetic explosion of high-energy materials to be realistically simulated and dynamic problems of materials and structures to be dealt with.

The combination of these different tools enables the behaviour of a material to be understood at the micro-, meso- and macro- levels, and structures to be correctly dimensioned by calculation.

Partnership

In its activities, the scientific world calls on cooperation, both national and international. The work involved is carried out in the laboratories of university research centres specialising in static and dynamic mechanical properties, with teams specializing in behavioural modelling: the CEA laboratory at Gramat for work on dynamic challenges and the French *ONERA* aerospace laboratories with its drop tower. These projects are carried on in close cooperation with companies working on the design and integration of equipment protection, including Nexter, MBDA, Sagem, Panhard, PGD and Renault Truck, among others, plus MSA Gallet for helmets, various suppliers of raw materials for ceramics and fibres, and an array of equipment manufacturers. The Saint-Louis Franco-German institute (ISL) is also a leading player in this area. This involves research and development activity which can take place in national centres of excellence such as the European ceramic centre Uptex.

The *DGA* also carries out research internationally and under this heading works on material in common with the United States, Great Britain, Germany and Israel. Work on structural integrity and survivability is not neglected either. European work on technologies to improve damage tolerance (specifically structural resistance to impact) is supported in association with the lightening of structures.

Future Armour

E.Petitpas, D.Vallée, B.Bettencourt

Nexter-Systems

Introduction

The role of armour is to protect a space against external attack. This space can be a construction, a vehicle, an aircraft, a ship, or indeed a person. The armour can take different forms depending on the volume to be protected, the type of threat, or indeed the coast authorized for the protection of the space.

Threats can take many forms, and can be split into eight categories:

- Kinetic projectiles, from small calibre rounds to large calibre flechettes;
- The hollow and formed charges in shells, rockets and missiles;
- Thermobaric charges in shells, rockets and missiles;
- Fragmentation charges in shells, rockets and missiles;
- Blast effect and formed charge mines;
- Fragmentation effect IEDs;
- Explosively formed penetrator (EFP) IEDs;

Blast effect IEDs.

The effects of these eight threat categories can be subdivided into two main groups:

- Local effect threats. These are kinetic energy projectiles, fragmentation IEDs, hollow charge and fragmentation effect shells, rockets and missiles. Their anti-armour action is limited to the local area at the point of impact;
- Global effect threats. Blast effect mines, blast effect IEDs, and thermobaric charges. All of these use the blast effect of explosives detonated at a limited distance from the space being protected. The armoured surface exposed to the blast effect is large, from one to several square meters;

Certain threats act both locally and globally. These include EFP mines and IEDs, and also fragmentation IEDs.

The technologies used for protection against these two groups of threats are very different:

- To protect against local effect threats we are looking for technologies which allow us to disturb the projectile enough for its energy is dissipated over as large a surface area as possible, in order to stop it;

- In the case of global effect threats, we seek to reduce its effects on the volume by reinforcing the mechanical structure and using protective shielding.

Global effect threat reduction

We try to minimise the shock wave transmitted by the geometry of the structure by using the deflecting effects of blast, transmitting it globally to the whole of the protected volume by avoiding local effects. The design effort is centred on the mechanical architecture of the space to be protected. In armoured vehicles, the mechanical designers play on the external shape of the vehicle to reduce the effect of blast, and in this way reduce the shock transmitted. This concerns bottom protection against mines, and shielding the space occupied by its wheels or tracks (together with the front and sides of the vehicle) against blast attack.

The bodywork must also be worked on to maximise its rigidity to blast, and its resistance to tearing. Further anti-blast protection fixed to the structure acts as an additional shield to protect vulnerable zones by absorbing some of the blast energy, and by transmitting the residual shock to the rigid zones of the bodywork.

In this way the protection of future armoured vehicles against the group of blast effects is developed using a combination of four planning principles:

- Controlling the interactions between blast effects and structures;

- Optimizing external forms of support structures (vehicle bodies, for example) to limit the transmission of shock effects;

- Optimizing the mechanical architecture of the vehicle body, to maximize both its rigidity and its resistance to extreme pressure;

- Designing additional protections which protect vulnerable zones by energy absorption, and the transmission of residual energy into the rigid zones of the bodywork.

In the future simulation will play a primordial role in developing the improvement of protection against the threat of blast effects. This will allow us to understand the phenomenon of interaction between blast effects and structures; to optimize shapes to limit shock transmission; to maximize rigidity and resistance; and to design protective shields and their links to the main structure.

Future materials to protect against global effect threats

Another way forward concerns research into protective materials.

A first approach involves those materials which are particularly energy-absorbent; the aim is to design protection systems which allow improvements to the functioning of energy shields. Elements currently available are combined in order to develop specific materials to achieve maximum energy absorption and the dissipation of residual energy over a maximum surface area. It seems more than likely that a future solution here may involve a porous or multi-layered material. Here too simulation will have an important role to play in the development of these complex materials.

A second approach is that of material solutions capable of absorbing shock waves: for example, the use of diphase materials, which can attenuate the shock waves produced by the explosion of a mine or IED. Porous materials, or materials of an equivalent structure, are potentially interesting solutions which work by a combination of impedance rupture and the dissipation of energy by vibration, deformation or the collapse of one of the phases. These solutions to attenuate explosion effects on various platforms are currently being studied.

Local effect threats

Here we are looking for technologies which perturb or damage the projectile, so as to dissipate its energy over the maximum possible area.

The great majority of plate armour gives only passive protection. Reactive armours have been developed and are used to mitigate specific threats, such as hollow charges. The principles of the various protective solutions can be split into five main categories:

- Projectile ricochet. Under certain conditions of projectile incidence, and of the hardness of the projectile relative to the surface being attacked, the projectile can ricochet and change trajectory. This very effective principle of protection can be used simply by sloping the protective plating. Its application is limited to sharply inclined surfaces such as the front glacis of armoured vehicles.

- Projectile deflection. This phenomenon has been observed on streamlined projectiles such as flechettes, when they penetrate special armours which are inclined relative to their trajectory. As the projectile penetrates the thickness of the protective material, an external rotation of the projectile occurs which tends to cause it to exit;

- Projectile interference. This effect is obtained on very thin projectiles, principally the jet of a hollow charge. The principle used is setting an armour plate in motion by a dynamic reaction of the plate with an underlying layer of either a passive elastomer-type material, or a reactive explosive. The first method concerns PAC armour (Plate Accelerated by Shock), the second reactive armour. These armours are currently in use on various vehicles, essentially for protection against hollow charges delivered by rocket, missile or shell.

- Projectile rupture. The break-up of a projectile on its impact with a very hard surface is a very effective way to dissipate its kinetic energy over a wider area. This method is used against kinetic energy projectiles such as flechettes, but above all against the less streamlined projectiles defined in STANAG 4569. The ideal solution is the fragmentation of the projectile against the protective armour, without penetration. Known as the 'Dwell' effect, it is observed against very hard ceramic-based armours: the projectile spreads over the surface of the ceramic without penetrating it.

- Projectile erosion. When armour hardness fails to break up the projectile, the aim of this technique is to stop it by eroding it as it traverses the armour material. Erosion occurs either by visco-plastic deformation, or by a mechanism of wearing. The first of these happens in metallic, and the second in ceramic armours.

In general, these methods of damaging projectiles are based on a combination of several materials whose complementary effects optimize the desired damaging effect. A classic combination is to superimpose a very hard material (such as a ceramic) and a layer of ductile material (such as a stratified composite) so as to allow the ceramic to fragment the projectile, while its fragments are blocked by the stratified composite.

Armour design must take into account both the various threats and the specification of the protection (angles of incidence, multi-impact etc). The most effective mechanisms of damage by projectile depend on the nature of the threats and the conditions of their impact on armour. For example:

- The deflection or ricochet of a streamlined projectile could be envisaged to protect a zone whose surface is highly inclined relative to the threat trajectory;

- Projectile fragmentation could be sought for those surfaces normal to the trajectory of highly hardened projectiles;

- The use of projectile erosion would be most effective against packaged IED or shell fragments.

Since 2000, the multiplication of threats (blasting and formed charge IEDs, in addition to traditional projectiles) and their incidences of attack on vehicles (all angles of attack must now be considered) have greatly complicated the design of armour. This must now combine several different ways of damaging projectiles, using the superposition of several different layers of material to optimize performance.

Bearing in mind the large number of parameters which must be taken into account, a priority for the design of future armours must be the mastery of simulation techniques for the various mechanisms of disruption and damage of projectiles, and for composite armours made up of different layers of material. This objective will demand a major effort to understand and model these mechanisms. Instrumented ballistic trials need to be developed in order to understand the mechanisms involved.

In parallel there is a need to develop behavioural and damage criteria to take account of damage mechanisms. Modelization at the mesoscopic level of material (that is to say, between the microscopic and macroscopic) will certainly be a future method. Dynamic trials on materials will permit the identification of the material parameters for the models which are developed.

This modelling will point us towards the right choice of those composite armour materials which will have an optimal counter-effect on projectiles. They will also allow us to think about the physical dimensioning of armour, leading to a choice of the solutions available for armour protection.

Perspectives for materials protecting against local effects

In parallel with the modelling effort, development will continue of materials with extreme properties; this will aid in the design of multi-material composite armour. Several avenues of research are being followed, some of which can come to fruition in the medium term, and others in the longer term.

In the medium term:

1- Research into very hard materials using new ceramics, or very fine grain ceramics; the use of nanoparticles of powder combined with their implementation using sintering flash techniques should result in increased hardness for classic ceramic materials;

2- Development of transparent ceramics. Transparent spinel (magnesium aluminium oxide) and sapphire ceramics have been produced experimentally in laboratory quantities; their ballistic properties have been evaluated, their performance being found to be comparable to classic ceramic armour. The use of these ceramics in the design of glass apertures would mark a spectacular bound forward in the ballistic performance of armoured glass. The current problem is the lack of an acceptably priced industrial process for the manufacture of the large-dimension plates which are needed.

3- Composite tissues have a three-dimensional architecture. They are made by weaving together fibres having tri-dimensional high resistance, and also have potential in the design of ballistic protection. Different architectures for 3D tissues are currently being investigated by a joint university/industry consortium.

4- Instantaneously hardening (rheo-thickening) fluids. These are obtained by the suspension of nanoparticles of mineral material in an organic liquid; the effect is a capability of hardening instantly under sudden pressure. These materials present us with a major opportunity for progress in the design of flexible shielding for personnel: the term 'liquid armour' is often used to describe the technology. Their use in body armour could revolutionize personnel protection.

In the longer term:

5- The development of materials which have progressive functionality. A combination of ceramic and metallic materials should lead to the reinforcement of the resistance to penetration of ceramic materials, and augment their ballistic performance. A joint research project involving French and Israeli teams is due to start this year.

6- Fibres with very high energy absorption capability. The synthesis of organic fibres based on carbon nanotube technology can lead to the development of fibres which will have a very high energy-absorption capability, exceeding even that of spider's web silk. These fibres could be very useful in the design of composite armour. A French laboratory is currently developing a pilot plant to manufacture them, and another is looking for ways to weave the end product.

7- Finally, several university laboratories are studying the properties of metallic glass.

Active protection systems

Between 1990 and 2005 research was undertaken in several countries into the concepts of active protection; its principle is the detection of the threat on its ballistic trajectory, and to neutralise or damage it by a pyrotechnic system prior to its impact. These systems have a spectrum of employment which is limited to rocket and missile threats, and are useless against other types of attack. Their innate complexity has led to the abandonment of research by the majority of companies and governments involved in their development. The one survivor is the Raphael *TROPHY* system, which is being trialled on Israeli army *MERKAVA* tanks.

Revue Défense Nationale is published by the Committee for National Defence Studies,
an association governed by the law of 1901, residing in the
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Editorial advisor: Olivier Kempf
Publicity managed by: BKSM Advertising - Tel: +33 (0)1 56 99 71 73
ISSN: 2105-7508 - CP N° 1014 G 85493 of 9 September 2010
Printed in France by Bialec, 95 boulevard d'Austrasie, BP 10423, 54001 Nancy cedex