Learning from Mother Nature:
Biomimicry for the Next Generation SAF

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Abstract:

This essay explores the possibilities of Biomimicry and how it can be harnessed by the Singapore Armed Forces (SAF). The usage of metallurgy in modern militaries appears to be devoid of a central essence and is often more a means to an end. Metallurgy works in binary terms; they either destroy or are destroyed, which does not reflect reality and nature's principles of growth and self-healing. However, the pursuit of biomimicry utilises innovative materials that injects life-like qualities into a weapon. This evolutionary bio-design is present in nature, not as a collection of parts but as a synthesis of a whole. As such, biomimicry may be a paradigm shift after metallurgy, in line with the humanity's quest of zealous discovery and technological advancement.

Keywords: Biomimicry, Technology, Harness, Combat Performance

INTRODUCTION

Animals have been man's best companion in warfare since ancient days. It was the cavalry horse, scout dog, messenger pigeon, amongst other animals that supported human warfare in the past millenniums.[1] However, the advent of metallurgy in warfare has displaced the now 'less reliable' animals with mechanical machines. Without metals, the materiel culture of society is unthinkable. Metallurgy is the basis for the production of the manufacturing, transportation and communications equipment, as well as for civil construction and military affairs.[2] What metallurgy gained in certainty, it lost in the human/animal touch and the unexplained irrational factors that animals deliver to the battlefield. As an old Chinese proverb goes – the warhorse was able to evade the enemy's pursuit independently and deliver its injured and even unconscious rider-owner back to base camp.

However, the utility of animals has not diminished, especially in situations when the operating terrain does not favour metallurgy. For example, during World War Two (WW II), American armoured units noted that the mountainous terrain and temperate forests in Sicily, Italy did not favour the mass use of armour.[3] Instead, the US forces adjusted and became mounted on horses. In the Asian theatre, the unorthodox combat unit, *'Merrill's Marauders'* used 340 horses and 360 mules to fight the Japanese in Burma.[4] The re-use of animals is not because of the immaturity of metallurgy. Most recently in the last Afghanistan war, the US Army Special Forces improvised and called for precision-guided munitions while riding on horses to battle against the Taliban forces in the mountainous terrain.[5]

Regardless of terrain, the lingering presence of animals is continually observed as an inspiration for military technologists throughout military history, and this trend is likely to continue. Biomimicry is the latest manifestation of this interdisciplinary introspection within academia-technologist community. Popularised around 1997 with the release of the book, *Biomimicry: Innovation inspired by Nature* by Janine M. Benyus, this burgeoning field will continue to serve future militaries. This essay seeks to explore the potential of biomimicry for the next generation SAF.[6]

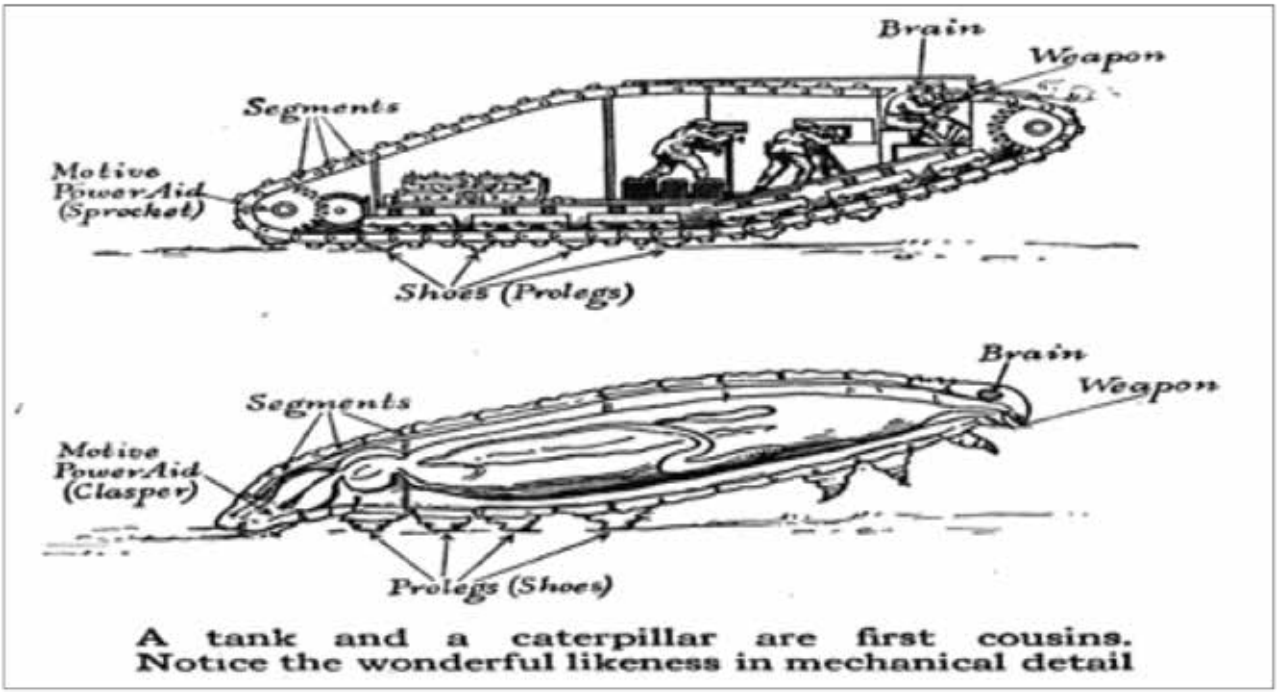

Figure 1: Prototype drawing of the 'Caterpillar tank'

DOMINANCE OF METALLURGY IN MODERN WARFARE

In modern militaries, most equipment are metallic. From precision strikes (small arms and large guns), to precision manoeuvres (soft and hard skin land vehicles, aircraft and ships) to precision information (ICK2 networks), all these equipment involve metals. Gone are the days where soldiers diligently practise martial arts to fight with spears in a phalanx formation or pikes (of which only the tip is metal) depending on the warrior culture and historical period. Metallurgy has now become the dominant paradigm in modern weapon technology.

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That said, metallurgy appears to be devoid of a central essence and is often more of a means to an end. Animal mimicry, on the other hand, has often inspired and influenced the design of modern war machines. For instance, with reference to Figure 1, the first generation tanks took inspiration from caterpillars.[7] Modern radar (range and detection) mimicked the sonar mechanism used by bats and dolphins.[8] The Wright brothers would not have invented the prototype aircraft in 1903 if they had not attempted to mimic birds in flight; even Leonardo da Vinci's 'Ornithopter' and the Greek mythological character, Daedalus' fashioned wings of wax, feathers and twine, were a mimicry of birds.[9] As such, metallurgy is the means but animal mimicry was likely the source of inspiration to that end.

However, metallurgy may be ending with diminishing returns, typical in the 'S' curve of the technology life cycle and in its sustenance.[10] Given the advances of high technology, metallurgy may have lost its lustre. From a capability perspective, metals are hard with titanium as its best, but the hardest substance on earth is synthetic diamonds which costs about 15% less than real diamonds.[11] If not for the

cost, we would be shooting diamonds! Moreover, metal may be hard but it is less flexible and not stealthy, from the electronic detection means. Conceptually from a paradigm perspective, metallurgy appears to work in binary terms—metallic platforms either shoot or get shot, they either destroy or are destroyed. There is no fuzzy middle, such as growing and self-healing after being hit, which is hardly representative of reality and nature. The golden question is, what is next after metallurgy?

POTENTIAL OF BIOMIMICRY TO BE UNLEASHED

Imagine the following scenario unfolding in a night urban operation in which you are a lone soldier tasked to capture a terrorist in a building: While making your way to the building, your clothing changes patterns in accordance to your surroundings just like a chameleon. Upon reaching the building, you climb like a gecko to the 3rd floor where the terrorist is hiding. Once inside the building, you scan around and like a snake, you are able to sense the image of your target in the darkness. You move towards your target but he shoots at you. Your spider silk inner armour does not take a dent but your outer abalone shell outer armour self-heals; and you are able to move near enough to stun your target like an electric eel and capture him. While you carry your target out, you are able to avoid all the improvised explosive devices (IEDs) planted through your sense of smell. While the painted scenario is hypothetical, it may become a reality not too far into the future with militaries adopting biomimicry.

From an evolutionary perspective, biomimicry could be seen as the next military innovation/ RMA that has its weaponry rigorously tested by nature; animals' evolutionary change involves constant iteraton with nature and reality and as Charles Darwin's dictum goes, 'only the fittest survives'. From this chain of logic, by adopting biomimicry, SAF is able to indirectly harness nature's evolutionary force for our force development.

The paradigm of metallurgy dominance has yet to shift. But if it does, biomimicry is a possible successor. Nevertheless, even if it is only a complement to metallurgy at present, it is useful to understand the philosophical underpinnings and specific areas of contributions that biomimicry can offer for the next generation SAF.

From a philosophical perspective, biomimicry can be said to represent (philosophical) holism because bio-design, at present in nature, is not a collection of parts but a synthesis of a whole.[12] This is philosophically in sync with the 'system of systems' thinking of the Revolution of Military Affairs (RMA) since the 1990s with Network Centric Warfare.[13] Philosophically, animals are by nature a complete ecosystem (system of systems) and studying how animals 'operate' will help find parallels to which military technology and weaponry could emulate. From an evolutionary perspective, biomimicry could be seen as the next military innovation/RMA that has its weaponry rigorously tested by nature; animals' evolutionary change involves constant iteraton with nature and reality and as Charles Darwin's dictum goes, 'only the fittest survives'. From this chain of logic, by adopting biomimicry, SAF is able to indirectly harness nature's evolutionary force for our force development. This is in stark contrast to metallurgy where linearity and philosophical individualism appear to prevail. A digress to contrast physics and biophysics is needed in order to illustrate this case in point. Physics describes brute strength. In linear terms, it theorises that a well-fed 60kg top-notch weightlifter can carry about 180kg of weights, typically 3 times one's body weight, in a clean and jerk manner.[14] However, the wonders of biophysics reveals that a leaf-clutter ant can carry 50 times its own weight, a male rhinoceros beetle 850 times and a tiny mite 1,180 times its own weight.[15] The exoskeleton and biophysical make-up of these insects which operate in hordes has tremendous implications

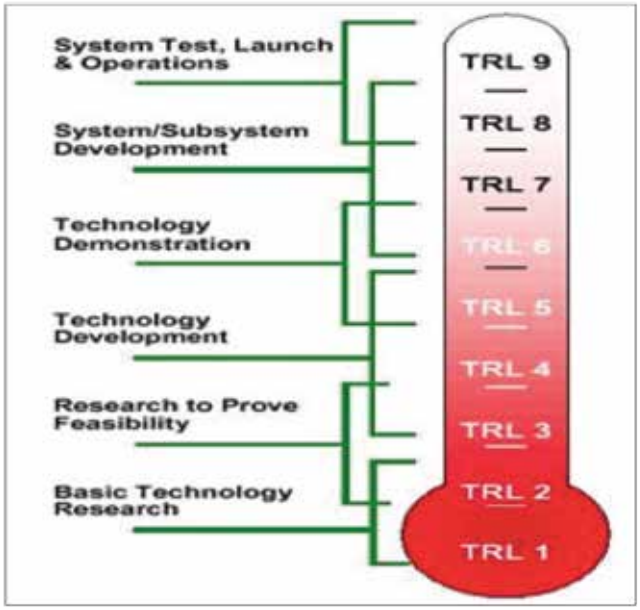

Figure 2: Technological Readiness Level

to military technology. Biophysics appears intriguing and full of potential.

A biomimicry design spiral, created by Carl Hastrich for the Biomimicry Institute is instructive to the holistic understanding of animals and derivation of implications for science and military technology.[16] The next section will discuss possible biomimicry ideas with respect to their Technological Readiness Level (TRL) for the next generation SAF. In Figure 2, the TRL is a measure used by selected United States (US) government agencies and many of the world's major companies and agencies to assess the maturity of evolving technologies, such as materials, components and devices, prior to incorporating that technology into a system or subsystem.[17]

BIOMIMICRY IN FUTURE ACTION (INDIVIDUAL SURVIVAL & PROTECTION)

Water Not Enough, No More.

Water is more critical than food. Humans die from dehydration within three to seven days, but can survive without food for more than 30-40 days. In battle, we must always foresee the scenario that an adversary will seek to cut off our lines of communications. Jungle survival skills teach us how to find water sources and drink from rivers using water purification tabs. However, what if there are no rivers and dynamic operations do not afford troops camping overnight to retrieve water from plants' condensation? Here, the Desert Beetles appear to have evolved a solution to this in the Namibian desert (see Figure 3). Though it lives in one of the driest deserts in the world, it is able to obtain all of the water it needs from the ocean fog due to the unique surface of its back. In the day, its matt black shell radiates heat; but at night, it becomes slightly cooler than its surroundings, causing fog to condense on its shell. In the morning, the beetle simply tips itself up, and lets the water trickle into its mouth. Designer Kitae Pak from the Seoul National University of Technology has designed the Dew Bank Bottle after the Desert Beetle and if further scaled down, it can enable war-fighters to harness water even in the most unlikely environments and empower our soldiers to fight and condense water on the move.[18]

Pixelated Camouflage Not Good Enough

In Soldiering 101, camouflage is used to prevent enemy detection. SAF has evolved from 1st to 2nd Generation camouflage, from using plants and synthetically pre-designed camouflage to digitally pixelated camouflage whose design has been proven by the US Marine Corps to play tricks with the human eye.[19] However, wearing the green pixelated uniform and fighting in an urban terrain do not intuitively translate to a sense of being 'protected' by the pixelated technology. Perhaps, the grey pixelated uniform would be useful in urban operations. However, it does not make logistical or operational sense to change from green to grey just before entering an urban terrain especially given the dynamic nature of next generation warfare whereby our soldiers are likely to have to fight in both urban and rural terrain interchangeably and in compressed tempo. Active or adaptive camouflage as inspired by chameleons and octopus is useful here. Chameleons [TRL: 4] and certain species of octopuses [TRL: 4] can alter their colour through the use of chromatophores that control the type and amount of light reflected. Work is being carried out by scientists at the Sandia National Laboratories in Albuquerque, New Mexico. The scientists have started to create a synthetic,

biomimetic material that will share the animals' ability to colour-shift. *"Military camouflage outfits that blend with a variety of environments without needing an outside power source - blue, say, when at sea, and then brown in a desert environment - is where this work could eventually lead to,"* says team leader George Bachand. [20]

BIO ARMOUR RULES FOR BOTH INDIVIDUAL AND PLATFORM PROTECTION

Currently, infantry soldiers wear heavy armour to protect against small arms fire, but this is at the expense of soldier mobility. Spiders offer a solution to light weight yet durable body armour. US scientists at the University of California have identified the genes and DNA sequences for two key proteins used in the 'dragline' silk of the tiny, but lethal, spiders found in the region. This discovery could lead to a variety of new materials for industrial, medical and military uses. Dragline silk from black widows [TRL: 4] is regarded as superior to that from other spiders because of its strength and extensibility, which enable the silk to absorb enormous amounts of energy. The silk's properties have interested the military, who are keen to explore the possibility of copying the structure of the silk for lightweight body armour.[21] This is not new per se given that what made the Mongols rule the steepe and the largest Empire in the world was their skill in horseback archery, manoeuvrist approaches and basic body armour of silk issued to every cavalry soldier.[22] As such, silk has already proven to be light enough yet resilient to protect themselves from enemy arrows. This Bio Armour is a new age rendition of that historical concept.

Figure 3. Desert Beetle and Dew Bank Bottle

Beyond lightness, the unique combination of fibre and exoskeleton in animals also prove to be useful if humans use exoskeleton to augment their human abilities. For instance, both the mantis shrimp [TRL: 4] and snail shell have [TRL: 3] inspired the composite use of hard ceramic and elastic organic materials. A partnership between Harvard University, the University of California and the Nanyang Technological University in Singapore has been established to study the makeup of the Mantis Shrimp's claw. They have found that the claw is made from a layer of very hard crystalline calcium-phosphate ceramic material that is about 60 µm thick. While it is actually quite fragile and would shatter on impact on its own, the team also discovered a much thicker region beneath it comprising layers of fibres made from an elastic material often found in sea fish exoskeletons. The team believed that the multiple layers of fibres have helped to prevent the claw from fracturing. With this design in mind, body armour could be designed in a similar way, using composites of hard ceramic and elastic organic materials.[23]

Besides Body Armour, Head Armour (helmet) is equally, if not more important since a head wound is an immediate evacuation from the battlefield. We often joke that 'one cannot think after putting on the helmet'. That is likely a comment in jest to illustrate the weight and discomfort from wearing a helmet, but the importance of a lightweight and durable helmet cannot be further underscored. Biophysical wonders in the woodpecker's skull design [TRL: 5], which enables it to withstand a shock of 60,000g of force without damaging the brain is useful here. Researchers at the University of California, Berkeley, have identified four designed safety features of woodpeckers. These four features combine to give strength and flexibility and yet minimise the transfer of vibrations as well as

reduce forces. These four features have been utilised in the design of new high impact products including crash helmets and flight data recorders.[24]

How about self-healing Armour? In metallurgy, the paradigm is binary opposites. Armour which has been destroyed has to be replaced entirely or risk being put out of action. But from a biological perspective, unless it is a serious third degree burn, the self-healing process of skin takes place. Such is the wonder of life—so why should our Armour be any different? The abalone shell [TRL: 4] is a case in point; besides being tasty, abalones shells are light yet extraordinarily tough—1,000 times more energy is required to break the shells than to fracture the toughest man-made ceramics. When cracked, the shells can even repair themselves. The abalone's toughness derives from layers of tiny calcium-carbonate plates that when struck, glide over one another to absorb the shock. If cracks develop, the plates simply grow back together. Princeton researchers are modelling the abalone's self-healing property in structures that can be built in space and similar principles could apply to military vehicles which are prone to damage in battle.[25]

BIOMIMICRY IN FUTURE ACTION (INDIVIDUAL COMBAT PERFORMANCE)

Scaling heights is No Longer a Feat

From an operational perspective, urban operations are difficult because buildings are hard to 'clear'. But a Gecko [TRL: 4] can scale up and down buildings effortlessly and its secret lies in the composite structure of its feet, on which every single toe pad is covered with millions of keratinous hair-like bristles called setae. Each seta in turn branches into hundreds of flat tips called spatulas, which make intimate contact with surfaces. This fibrillar array achieves adhesion primarily by non-covalent van der Waals forces between the spatulas and the surface. Theoretical van der Waals gloves could generate an adhesion force comparable to the body weight of 500 men.[26] If it was integrated into an Ant exoskeleton, it would grant tremendous strength, which one could scale buildings easily. Imagine how fast the SAF could clear buildings during Urban Operations.

'Who Says Dark Cannot Shoot!'

Currently, militaries fight with infra-red goggles but it frequently gets foggy in our tropical climate when we sweat, even at night! Bats [TRL: 6] use echo-location and snakes use pit organs to feel the presence of warm bodies. Based on the echo-location used by bats to find their way and avoid even small objects in total darkness, the UltraCane was developed to assist the vision impaired to find their way. It was designed and manufactured by Sound Foresight and uses sound waves to locate objects in front of the user. A small electronic echo-location device is attached to a white cane and provides sensory feedback through the cane's handle.[27] While this is currently used for the visually impaired, it could be adapted for soldiers who typically need to operate in the dark. If it is fashioned to work in combination with a soldier's weapon, the soldier could potentially find his way in the darkness and shoot instantly. In another study, scientists have discovered that vipers, pythons and boas [TRL: 3] have holes on their faces called pit organs, which contain a membrane that can detect infrared radiation from warm bodies up to one metre away. At night, these pit organs allow snakes to 'see' an image of their predator

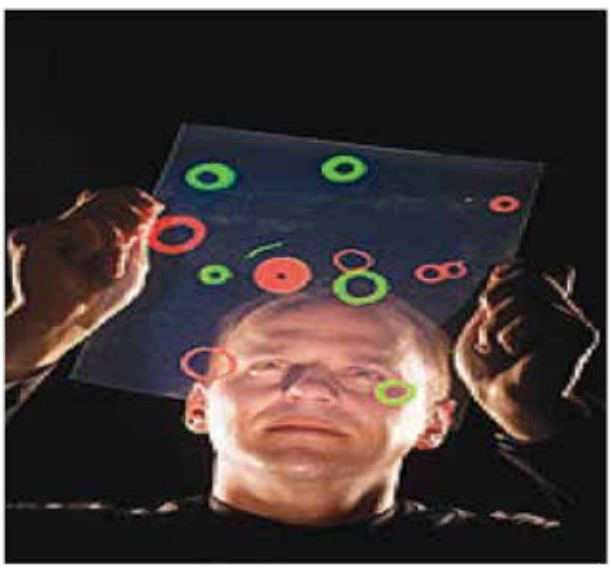

Figure 4. Sandia researcher George Bachand examines an enlargement of actual images of light-emitting quantum dots

or prey. This is akin to an infrared camera and may allow soldiers to see through camouflage that may fool the eyes.[28] This combination of localisation senses can complement our infra-red goggles to help SAF fight better in the dark and even through foliage (Foliage Penetration - FOPEN).

BIOMIMICRY IN FUTURE ACTION (SYSTEMS WARFARE)

Intelligence Warriors in the Animal Kingdom

Current militaries' intelligence assets composed largely of assets that extend the coverage of sight and sound beyond human limitations. With technological improvements, collection assets have reduced in size and improved in durability. However, this may pale in comparison to what the Animal Kingdom can deliver. Imagine, the Kingdom's Unmanned Aerial Vehicles (UAVs) are but flies [TRL: 8] which can take off and land in any direction, change course in just 30 thousandths of a second. It can use three different wing motions to create backspin and air vortices that create lift.[29] Land reconnaissance, bomb diffusion and counter-mining operations can be done by cockroaches [TRL: 5], who are apt in manoeuvring in different terrains undaunted by hip-height obstacles and slopes of up to 24 degrees.[30] They can be augmented by lobsters[31], [TRL: 4] for sea and land operations and silk-moths[32] [TRL: 3] for air operations, both of whose olfactory faculty are advanced enough to sniff out friends, foes and TNT. Lastly, imagine a horde of sand fleas [TRL: 4] jumping forward 30 feet into the air in cadence. The amount of comprehensive battlefield awareness would be unprecedented if the imagery captured by each sand flea is pieced together to form a macro-picture.[33] These are ideas that military nano technology can be developed further.

Or, what about the auto-sensing of chemical and biological threats? Here, the sensing capabilities of the Morphos butterfly [TRL:5] is a useful case in point. The Defence Advanced Research Projects Agency (DARPA) had awarded General Electric a $6.3 million grant to further develop a project to replicate the nano-structures from the wing scales of butterflies into sensors. Research has uncovered that the scales on Morphos butterfly wings can pick out molecules from the atmospheric noise. Such sensors could be embedded in clothing and tuned to change colour upon detection of a chemical or biological threats.[34]

Electronically Stealth Warfare for our Metallurgy

Modern warfare overly focuses on metallurgy and its natural nemesis is the radar. All metals will have a radar cross section (RCS) that 'bounces back' the radio waves to expose one's presence. Modern technology has tried to reduce this RCS through more graphite-based advanced materials, rounder edges and painting surfaces to absorb radiation, but RCS is still present.[35] All moths have anti-reflective (AR) surfaces and have inspired the creation of anti-reflective, radio frequency transparent windows. The surface of a moth's cornea consists of tiny protruding bumps that exist to keep moths safe from predators, by preventing light from reflecting in their eyes and betraying their presence. Mark Mirotznik, from the University of Delaware, has adapted these AR ideas and created special surfaces in which microwave energy is transmitted with very little reflections over large ranges of frequency or bandwidths. Special windows can then be created which can enable an antenna system within to transmit, yet at the same time prevent radar detection. [TRL: 4][36]

Unmanned Warfare – the 'Animal' Way

Unmanned warfare is the latest fad in warfare. UAV drones allegedly spied on Osama bin Laden the night before the special operations raid that killed him in Pakistan.[37] Our Combat Engineers use robots as unmanned land vehicles to assist in Chemical, Biological, Radiological and Explosive (CBRE) operations. Now, imagine unmanned land vehicles as fast as the cheetah and armed with weaponry. The cheetah is the fastest land animal with a sleek body that is built for speed. It is also the name for a four-legged robot under development by Boston Dynamics, which can run faster than humans. DARPA awarded the company a contract to build a faster, more fearsome animal-like robot. Boston Dynamics has envisioned Cheetah performing military operations

Figure 5. Boston Dynamics' Cheetah Robot

with excellence, with its incredible agility to make tight turns so that it can zigzag to chase and evade and have the ability to stop suddenly. [TRL: 8][38]

Cyber Defence – the 'Ant' Way

Information Knowledge-Enabled Command and Control (IKC2) and Network-Centric Warfare are about networked-enabled warfare where precise information manoeuvres and fires are made possible by Information Communication Technology (ICT). The flip side of it is that adversaries only need to cripple one's IT systems to disable its military. Hence, Cyber Defence is important and the SAF has also recently announced its focus in this area.[39] The operating concept of Ants can inspire us on this security journey. By looking at the way ants call for backup and overpower invaders through sheer quantity of soldiers, security experts have devised the 'digital ant' [TRL: 6], that will help human operators spot threats to computer systems more quickly. Unlike traditional security devices, which are static, these 'digital ants' wander through computer networks looking for threats, such as 'computer worms'—self-replicating programmes designed to steal information or facilitate unauthorised use of machines. When a 'digital ant' detects a threat, an army of ants will converge at the location and help draw the attention of human operators who can step in to investigate. Whenever a 'digital ant' identifies some evidence, it is programmed to leave behind a stronger scent to attract more ants and thus produce the swarm that marks a potential computer infection. So far, experiments with the 'digital ants' have been successful. The technology fits best for large computer networks for corporations, universities and militaries. Soon, we may just owe the security of our computers to the often underestimated 'digital ant.'[40]

Biomimicry presents exciting possibilities for military technology and is an unconventional form of technology that the next generation SAF should keep a watch on.

WHITHER PARADIGM SHIFT FOR NEXT GENERATION MILITARIES?

Biomimicry presents exciting possibilities for military technology and is an unconventional form of technology that the next generation SAF should keep a watch on. However, biomimicry is not without its challenges. Akin to most Research and Development (R&D) efforts, extensive resources such as time and money are essential. And yet, results may be uncertain even with an abundance of these as there are many uncertainties in learning from nature, which is a whole system by itself.

Notwithstanding its challenges, the 3rd Generation SAF can consider experimenting with some of the seed ideas in our local context. To enable this, military technologists can take up roles akin to DARPA to bridge research between academia, commercial companies and the military. Collaborations through these networks will better allow the SAF to survey biomimicry ideas and technologies and customise them to local needs. To this end, Future Systems and Technology Directorate (FSTD) is well-poised for this role.

Whether biomimicry will prove to be the next paradigm shift after metallurgy will depend on the FSTDs around the world and their diligence in breaking through the mindset that warfare involving metallurgy and fires is the most reliable mode. This assumption may no longer be relevant. When China invented fire powder and used it for celebratory fireworks in the Song dynasty, the Europeans were happily fighting with pikes and swords in the Middle Ages.[41] It was the

curiosity and willingness to venture into uncharted waters that enabled these scientific breakthroughs. The same can be same for the invention of the atomic bomb during WW II. One thing is clear: nature is unique and wonderful. Learning from and about nature, since the Age of Enlightenment, has led to immense knowledge creation of the modern day. The attempt to adopt biomimicry for the next generation SAF is in line with this never-ending human quest of introspective learning and zealous discovery.

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