99% (Biological) Inspiration …

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Abstract. Greater understanding of biology in modern times has enabled significant breakthroughs in improving healthcare, quality of life, and eliminating many diseases and congenital illnesses. Simultaneously there is a move towards emulating nature and copying many of the wonders uncovered in biology, resulting in "biologically inspired" systems. Significant results have been reported in a wide range of areas, with systems inspired by nature enabling exploration, communication, and advances that were never dreamed possible just a few years ago. We warn, that as in many other fields of endeavor, we should be *inspired* by nature and biology, not engage in mimicry. We describe some results of biological inspiration that augur promise in terms of improving the safety and security of systems, and in developing self-managing systems, that we hope will ultimately lead to self-governing systems.

1 Introduction

Thomas Alva Edison described invention as 1% inspiration and 99% perspiration. This quotation is attributed to him with multiple variations, some describing invention, others describing genius.*

We cannot possibly hope to match the inventiveness and genius of nature. We can be *inspired* by nature and influenced by it, but to attempt to mimic nature is likely to have very limited success, as early pioneers of flight discovered.

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[*] The earliest recorded quotation is from a press conference, quoted by James D. Newton in *Uncommon Friends* (1929): "None of my inventions came by accident. I see a worthwhile need to be met and I make trial after trial until it comes. What it boils down to is one per cent inspiration and ninety-nine per cent perspiration."

Icarus attempted to escape the Labyrinth in which he was imprisoned with his father, Daedalus, by building wings from feathers and wax. Despite Deadalus's warning not to fly so low as to get the feathers wet, nor so near the sun as to melt the wax, Icarus flew too high, the wax did indeed melt, and he fell to his death.

In 1809, a Viennese watchmaker named Degen claimed to have flown with similar apparatus. In reality, he only hopped a short distance, and was supported by a balloon. Early attempts at mechanical flight involved the use of aircraft with wings that flapped like a bird's. But clearly, trying to copy birds was not going to work:

> Since the days of Bishop Wilkins the scheme of flying by artificial wings has been much ridiculed; and indeed the idea of attaching wings to the arms of a man is ridiculous enough, as the pectoral muscles of a bird occupy more than two-thirds of its whole muscular strength, whereas in man the muscles, that could operate upon wings thus attached, would probably not exceed one-tenth of his whole mass. There is no proof that, weight for weight, a man is comparatively weaker than a bird … [1].

It was only when inventors such as Otto Lilienthal, building on the work of Cayley, moved away from directly mimicking nature, and adopted fixed wings, originally as gliders and later as monoplanes, and eventually as aircraft with wings and a tail, as Cayley had identified was needed for flight [2], that success was achieved [1]. Even then, early aircraft had very limited success (the Wright brothers' historic first powered flight at Kitty Hawk, North Carolina, in 1903 only lasted 12 seconds and 120 feet [3]), and required the addition of gas-powered engine for thrust and the Wright brothers' identification of an effective means of lateral control, for a feasible heavier-than-air craft to be possible.

Aircraft as we know them now bear very little resemblance to birds. Flight was *inspired* by nature, but hundreds of years were spent trying to copy nature, with little success. Inspiration was vital—otherwise man would never have attempted to fly. But direct mimicry was the wrong direction. Similarly we believe that computing systems may benefit much by being *inspired* by biology, but should not attempt to copy biology slavishly.

To invent an airplane is nothing.
To build one is something.
But to fly is everything.
Otto Lilienthal (1848-1896)

2 Biologically-Inspired Computing

We've discovered the secret of life.
Francis Crick (1916-2004)

The Nobel prize-winning discovery, in 1953, of the double helix structure of DNA and its encoding was revolutionary. It has opened a whole new world of understanding of biology and the way in which nature works. Simultaneously, it has resulted in several new fields of scientific research: genetics, genomics, computational biology, and bioinformatics, to name but a few.

The understanding of how nature encodes biological information and determines how living organisms will develop and evolve has enabled us to improve the quality of life, eliminate certain diseases, cure congenital defects in unborn children, and make significant advances in controlling and eventually eliminating life-threatening conditions.

This greater understanding of the biology of living organisms has also indicated a parallel with computing systems: molecules in living cells interact, grow, and transform according to the "program" dictated by DNA. Indeed, the goal of bioinformatics is to develop "in silico" models of in vitro and in vivo biological experiments [4].

Paradigms of Computing are emerging based on modeling and developing computer-based systems exploiting ideas that are observed in nature. This includes building self-management and self-governance mechanisms that are inspired by the human body's autonomic nervous system into computer systems, modeling evolutionary systems analogous to colonies of ants or other insects, and developing highly-efficient and highly-complex distributed systems from large numbers of (often quite simple) largely homogeneous components to reflect the behavior of flocks of birds, swarms of bees, herds of animals, or schools of fish.

This field of "Biologically-Inspired Computing", often known in other incarnations by other names, such as: Autonomic Computing, Organic Computing, Biomimetics, and Artificial Life, amongst others, is poised at the intersection of Computer Science, Engineering, Mathematics, and the Life Sciences [5]. Successes have been reported in the fields of drug discovery, data communications, computer animation, control and command, exploration systems for space, undersea, and harsh environments, to name but a few, and augur much promise for future progress [5, 6].

3 The Autonomic Nervous System

> The nervous system and the automatic machine are fundamentally alike in that they are devices, which make decisions on the basis of decisions they made in the past.
>
> *Norbert Weiner (1894-1964)*

Inspiration from human biology, in the form of the autonomic nervous system (ANS), is the focus of the Autonomic Computing initiative. The idea is that mechanisms that are "autonomic", in-built, and requiring no conscious thought in the human body are used as inspiration for building mechanisms that will enable a computer system to become self-managing [7].

The human (and animal) body's *sympathetic nervous system (SyNS)* deals with defense and protection ("fight or flight") and the *parasympathetic nervous system (PaNS)* deals with long-term health of the body ("rest and digest"), performing the vegetative functions of the body such as circulation of the blood, intestinal activity, and secretion of chemicals (hormones) that circulate in the blood. So too an autonomic system tries to ensure the continued health and well-being of a computer-based system by sending and monitoring various signals in the system.

The general properties of an autonomic (self-managing) system can be summarised by four objectives: being self-configuring, self-healing, self-optimizing and self-protecting, and four attributes: self-awareness, self-situated, self-monitoring and self-adjusting (Figure 1). Essentially, the objectives represent broad system requirements, while the attributes identify basic implementation mechanisms [8].

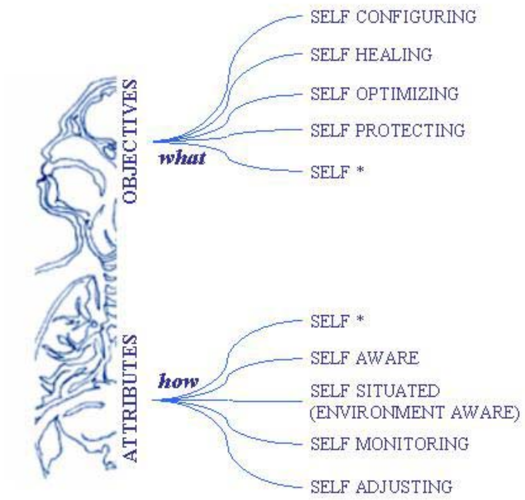

Fig. 1 Autonomic System Properties

In achieving such self-managing objectives, a system must be aware of its internal state (self-aware) and current external operating conditions (self-situated). Changing circumstances are detected through self-monitoring, and adaptations are made accordingly (self-adjusting). As such, a system must have knowledge of its available resources, its components, their desired performance characteristics, their current status, and the status of inter-connections with other systems, along with rules and policies of how these may be adjusted. Such ability to operate in a heterogeneous environment will require the use of open standards to enable global understanding and communication with other systems [5].

These mechanisms are not independent entities. For instance, if an attack is successful, this will necessitate self-healing actions, and a mix of self-configuration and self-optimization, in the first instance to ensure dependability and continued operation of the system, and later to increase self-protection against similar future attacks. Finally, these self-mechanisms should ensure that there is minimal disruption to users, avoiding significant delays in processing.

At the heart of the architecture of any autonomic system are sensors and effectors. A control loop is created by monitoring behavior through sensors, comparing this with expectations (knowledge, as in historical and current data, rules and beliefs), planning what action is necessary (if any), and then executing that action through effectors. The closed loop of feedback control provides the basic backbone structure for each system component [9].

The autonomic environment requires that autonomic elements and, in particular, autonomic managers for these elements communicate with one another concerning self-* activities, in order to ensure the robustness of the environment. Figure 2 depicts that the autonomic manager communications (AM⇔AM) also includes a reflex signal. This may be facilitated through the additional concept of a pulse monitor—PBM (an extension of the embedded system's heart-beat monitor, or HBM, which safeguards vital processes through the emission of a regular "I am alive" signal to another process) with the capability to encode health and urgency signals as a pulse [10]. Together with the standard event messages on the autonomic communications channel, this provides dynamics within autonomic responses and multiple loops of control, such as reflex reactions among the autonomic managers. This reflex component may be used to safeguard the autonomic element by communicating its health to another AE. The component may also be utilized to communicate environmental health information.

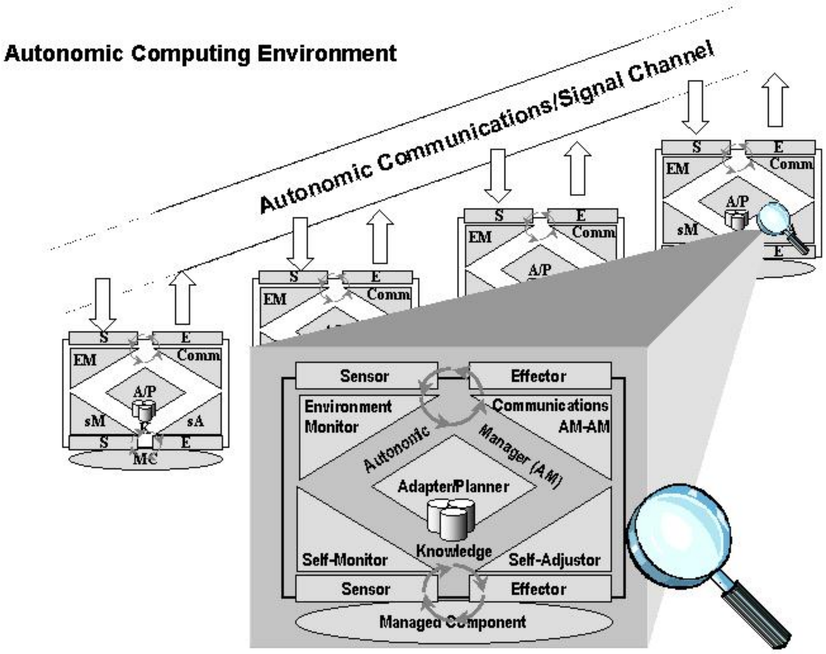

Fig. 2 Autonomic System Environment consisting of Autonomic Elements

An important aspect concerning the reflex reaction and the pulse monitor is the minimization of data sent—essentially only a "signal" is transmitted. Strictly speaking, this is not mandatory; more information may be sent, yet the additional information must not compromise the reflex reaction. For instance, in the absence of bandwidth concerns, information that can be acted upon quickly and not incur processing delays could be sent. The important aspect is that the information must be in a form that can be acted upon immediately and not involve processing delays (such as is the case of event correlation) [11].

Just as the beat of the heart has a double beat ("lub-dub", as it is referred to by the medical profession) the autonomic element's pulse monitor may have a double beat encoded—a *self* health/urgency measure and an *environment* health/urgency measure

[12]. These match directly with the two control loops within the AE, and the self-awareness and environment awareness properties.

4 Inspiration from Human Biology

> We still do not know one thousandth of one percent of what nature has revealed to us.
> *Albert Einstein (1879-1955)*

4.1 New Metaphors

In this emerging field of biologically-inspired computing, we are seeking inspiration for new approaches from (obviously, pre-existing) biological mechanisms, and in fact a whole plethora of further self-* properties are being proposed and developed, leading to the coining of the term *selfware*.

The biological cell cycle is often described as a circle of cell life and division. A cell divides into two "daughter cells" and both of these cells live, "eat", grow, copy their genetic material and divide again producing two more daughter cells. Since each daughter cell has a copy of the same genes in its nucleus, daughter cells are "clones" of each other. This "twinning" goes on and on with each cell cycle. This is a natural process.

Very fast cell cycles occur during development causing a single cell to make many copies of itself as it grows and differentiates into an embryo. Some very fast cell cycles also occur in adult animals. Hair, skin and gut cells have very fast cell cycles to replace cells that die naturally. Scientists now believe that some forms of cancer may be caused by cells not dying quickly enough, rather than cycling out of control.

But there is a kind of "parking spot" in the cell cycle, called "quiescence". A *quiescent* cell has left the cell cycle; it has stopped dividing (Figure 3). Quiescent cells may re-enter the cell cycle at some later time, or they may not; it depends on the type of cell. Most nerve cells stay quiescent forever. On the other hand, some quiescent cells may later re-enter the cell cycle in order to create more cells (for example, during pubescent development) [13].

We have been considering self-destruction as a means of providing an intrinsic safety mechanism against non-desirable emergent behavior from the selfware. It is believed that a cell knows when to commit suicide because cells are programmed to do so—self-destruction (sD) is an intrinsic property. This sD is delayed due to the continuous receipt of biochemical retrieves. This process is referred to as *apoptosis*, meaning "drop out", used by the Greeks to refer to the Autumn dropping of leaves from trees; i.e., loss of cells that ought to die in the midst of the living structure. The process has also been nicknamed "death by default" where cells are prevented from putting an end to themselves due to constant receipt of biochemical "stay alive" signals.

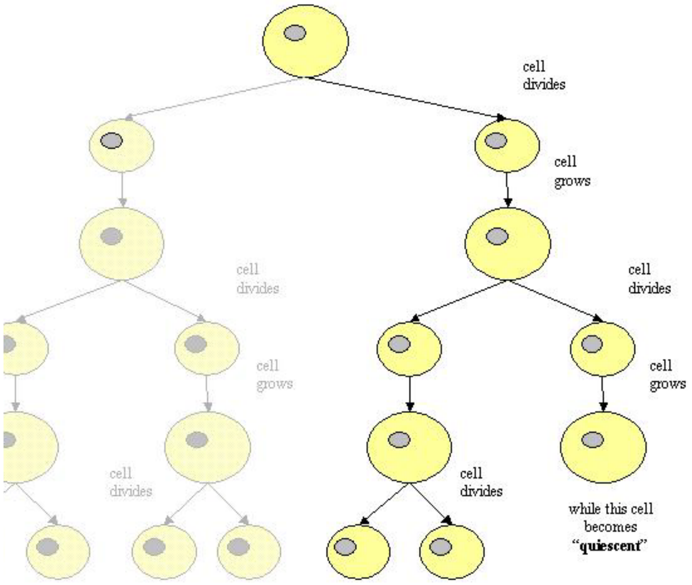

Fig. 3 Cycle of cell life - featuring a quiescent cell

Further investigations into the apoptosis process have discovered more details about the self-destruct program. Whenever a cell divides, it simultaneously receives orders to kill itself. Without a reprieve signal, the cell does indeed self-destruct. It is believed that the reason for this is self-protection, as the most dangerous time for the body is when a cell divides, since if just one of the billions of cells locks into division the result is a tumor, while simultaneously a cell must divide to build and maintain a body [14, 15, 16].

4.2 Inspiration

Of course, each of these techniques and mechanisms is useful in achieving autonomicity and in mimicking the autonomic nervous system (ANS). But while the inspiration comes substantially from that of the human (or animal) body, the techniques are not those that the ANS actually uses.

There *are* signals sent around the human body in the form of hormones and pulses, amongst others, in the blood. But in modern computer science and engineering, we have developed many efficient communication mechanisms that do not rely on signals flowing through miles of unnecessary channels (veins and arteries), but may be directly routed or broadcast using wireless communications.

We do not know precisely how apoptosis and quiescence works, nor specifically their roles. But they certainly offer interesting ideas for future security and safety mechanisms in computer-based systems [6].

These techniques are *inspired* by nature, but not necessarily implemented as they are by nature. In many cases, we can make some optimizations or improvements; in other cases we simply do not understand enough of how nature works to implement these directly, but they can certainly inspire interesting metaphors for self-management and self-governance.

5 Swarms

> What is not good for the swarm is not good for the bee.
> *Marcus Aurelius (A.D. 121-180)*

We are all familiar with swarms in nature. The mere mention of the word "swarm" conjures up images of large groupings of small insects, such as bees (apiidae) or locusts (acridiidae), each insect having a simple role, but with the swarm as a whole producing complex behavior.

Strictly speaking, such emergence of complex behavior is not limited to swarms, and we see similar complex social structures occurring with higher order animals and insects that don't swarm *per se*: colonies of ants, flocks of birds, packs of wolves, etc. These groupings behave like swarms[†] in many ways [17].

A *swarm* consists of a large number of simple entities that have local interactions (including interactions with the environment) [29]. The result of the combination of simple behaviors (the microscopic behavior) is the emergence of complex behavior (the macroscopic behavior) and the ability to achieve significant results as a "team" [18]. Basing collaborative computing systems on the concept of a swarm allows us to build complex systems, with often surprising behavior, from simple components.

Intelligent swarm technology is based on swarm technology where the individual members of the swarm also exhibit independent intelligence [19]. Intelligent swarms may be homogeneous or heterogeneous, or may start out as homogeneous and evolve as in different environments they "learn" different things, develop new (different) goals, and eventually become heterogeneous, reflecting different capabilities and a societal structure.

Agent swarms have been used as a computer modeling technique and have also been used as a tool to study complex systems [20]. Examples of simulations that have been undertaken include flocks of birds as well as business and economics and ecological systems.

In *swarm simulations*, each of the agents is given certain parameters that it tries to maximize. Swarm simulations have been developed that exhibit unlikely emergent behavior. These emergent behaviors are the sums of often simple individual behaviors, but, when aggregated, form complex and often unexpected behaviors.

Swarm intelligence techniques (note the slight difference in terminology from "intelligent swarms") are population-based stochastic methods used in combinatorial

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[†] The term "swarm", as we use it here, refers to a (possibly large) grouping of simple components collaborating to achieve some goal and produce significant results. The term should not be taken to imply that these components fly (or are airborne); they may equally well be on the surface of the Earth, under the surface, under water, or indeed operating on other planets.

optimization problems, where the collective behavior of relatively simple individuals arises from their local interactions with their environment to give rise to the emergence of functional global patterns.

Swarm robotics refers to the application of swarm intelligence techniques to the analysis of swarms where the embodiment of the "agents" is as physical robotic devices.

5.1 Swarm Inspiration

The idea that swarms can be used to solve complex problems has been taken up in several areas of computer science. These include the use of analogies to the pheromone trails used by ants (to leave trails for the colony to follow to stores of food) in software to solve the traveling salesman problem, allowing the software to "find" the shortest route by following the route with the most "digital pheromone", meaning it is the shortest (as on longer routes the concentration of pheromone would be lower due to being spread over a greater distance) [17, 21]. The approach is an example of *Ant Colony Optimization*, a very interesting approach that is inspired by the social behavior of ants, and uses their behavior patterns as models for solving difficult combinational optimization problems [22].

Swarm behavior is also being investigated for use in such applications as telephone switching, network routing, data categorizing, and shortest path optimizations. Swarm radio and "swarmcasting" of television over the internet is an approach to file-sharing that is inspired substantially by swarms. The approach exploits under-utilized uplinks to download part of the file to other users and then allow for the receipt of portions of the file from those users. The result is that streaming video is possible even without a high-speed internet connection.

Research at Penn State University has focused on the use of particle swarms for the development of quantitative structure activity relationships (QSAR) models used in the area of drug design [23]. The research created models using artificial neural networks and k-nearest neighbor and kernel regression. Binary and niching particle swarms were used to solve feature selection and feature weighting problems.

Particle swarms have influenced the field of computer animation also. Rather than scripting the path of each individual bird in a flock, the Boids project [24] elaborated a particle swarm with the simulated birds being the particles. The aggregate motion of the simulated flock is much like that in nature: it is the result of the dense interaction of the relatively simple behaviors of each of the (simulated) birds, where each bird chooses its own path.

5.2 Swarms for Exploration

NASA is investigating the use of swarm technologies for the development of sustainable exploration missions that will be autonomous and exhibit autonomic properties [25]. The idea is that biologically-inspired swarms of smaller spacecraft offer greater redundancy (and, consequently, greater protection of assets), reduced costs and risks, and the ability to explore regions of space where a single large spacecraft would be impractical.

ANTS is a NASA concept mission, a collaboration between NASA Goddard Space Flight Center and NASA Langley Research Center, which aims at the development of revolutionary mission architectures and the exploitation of artificial intelligence techniques and the paradigm of biological inspiration in future space exploration. The mission concept includes the use of swarm technologies for both spacecraft and surface-based rovers, and consists of several submissions:

- *SARA: The Saturn Autonomous Ring Array* will launch 1000 pico-class spacecraft, organized as ten sub-swarms, each with specialized instruments, to perform *in situ* exploration of Saturn's rings, by which to understand their constitution and how they were formed. The concept mission will require self-configuring structures for nuclear propulsion and control, which lies beyond the scope of this paper. Additionally, autonomous operation is necessary for both maneuvering around Saturn's rings and collision avoidance.
- *PAM: Prospecting Asteroid Mission* will also launch 1000 pico-class spacecraft, but here with the aim of exploring the asteroid belt and collecting data on particular asteroids of interest for potential future mining operations.
- *LARA: ANTS Application Lunar Base Activities* will exploit new NASA-developed technologies in the field of miniaturized robotics, which may form the basis of remote landers to be launched to the moon from remote sites, and may exploit innovative techniques to allow rovers to move in an amoeboid-like fashion over the moon's uneven terrain.

5.3 Inspiration and Improvement

ANTS, although a nice acronym, is actually somewhat of a misnomer—other than the LARA submission, the concept mission is more inspired by swarms of bees or flocks of birds than by colonies of ants.

But even then, ANTS is merely *inspired* by birds and bees. As we discussed in Section 1, the pioneers of flight found that directly attempting to mimic avian flight was the wrong way forward. Similarly, ANTS spacecraft in the PAM and SARA submissions will not attempt to fly like birds (in any case it would not be practical to build them with wings, a short tail, a curved sternum and hollow bones, in the way birds have evolved from *Archaeopteryx,* a dromaeosaurid from the late Jurrasic and Cretaceous periods and the earliest known flying creature).

In PAM, illustrated in Figure 4, a swarm of autonomous pico-class (approximately 1kg) spacecraft will explore the asteroid belt for asteroids with certain characteristics. In this mission, a transport ship, launched from Earth, will travel to a point in space where gravitational forces on small objects (such as pico-class spacecraft) are all but negligible. From this point, termed a Lagrangian, 1000 spacecraft, which will have been assembled *en route* from Earth, will be launched into the asteroid belt.

Approximately 80 percent of the spacecraft will be workers that will carry the specialized instruments (e.g., a magnetometer or an x-ray, gamma-ray, visible/IR, or neutral mass spectrometer) and will obtain specific types of data. Some will be coordinators (called leaders) that have rules that decide the types of asteroids and data the mission is interested in and that will coordinate the efforts of the workers. The third type of spacecraft are messengers that will coordinate communication between the rulers and workers, and communications with the Earth ground station.

The swarm will form sub-swarms under the control of a ruler, which contains models of the types of science that it wants to perform. The ruler will coordinate workers, each of which uses its individual instrument to collect data on specific asteroids and feed this information back to the ruler, who will determine which asteroids are worth examining further. If the data matches the profile of a type of asteroid that is of interest, an imaging spacecraft will be sent to the asteroid to ascertain the exact location and to create a rough model to be used by other spacecraft for maneuvering around the asteroid. Other teams of spacecraft will then coordinate to finish mapping the asteroid to form a complete model.

This is *not* how birds flock nor bees swarm.[‡] Birds form flocks in response to a *flocking call* issued by one of the birds. Birds in the flock continue in the flight pattern by “following” another bird. It is thought that collisions are avoided via *flight calls*, whereby birds let other birds know where they are via sound. In ANTS, the spacecraft do not “broadcast” in this way; spacecraft do not communicate with each other directly, but rather via a *messenger* that coordinates communications between the spacecraft and with Earth. Collision-avoidance (both collisions with other spacecraft and with asteroids) in ANTS is achieved by keeping models of locations, which will be achieved via various means. Since movement will be enabled only by simple thrusters, it is anticipated that many of the spacecraft will be lost due to collisions.

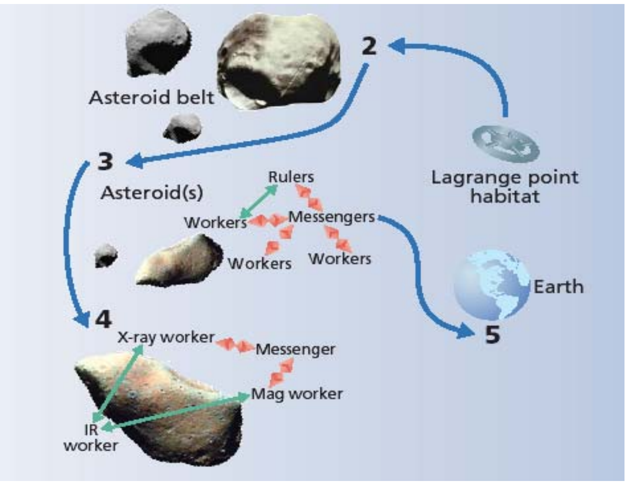

Fig. 4 ANTS PAM (Prospecting Asteroid Mission) scenario

In many senses, this is more efficient than the broadcast mechanism of the flocking calls and flight calls. There is less communication overhead, and the spacecraft are not continually having to update the information on where other spacecraft are located relative to them. Of course we can tolerate certain losses of spacecraft (one of the motivations for a swarm-based approach is to have redundancy and avoid mission loss due to a single incident), as long as the number of incidents is within certain boundaries, whereas a flock of birds could not tolerate continual losses due to collisions.

[‡] Not all species of bee swarm; there are several solitary species.

ANTS spacecraft will also need to have protection mechanisms built in, such as going into sleep mode to protect solar sails (used for power) during solar storms. This is analogous to a flock of birds taking shelter in severe weather, but the spacecraft do not have to land and find shelter, they merely have to alter their position and lower their sails to avoid damage from electrical charges, etc.

Similarly, flocks of birds and swarms of bees do not form sub-swarms as is envisioned in ANTS, nor do they take instructions directly from a leader. While flocks and swarms in nature do occasionally allow for an alternate to take over a particular role (e.g., the establishment of a new queen in a hive), this is not so efficient as in ANTS where a worker with a damaged instrument, instead of becoming useless, can take over the role of messenger, or even leader.

The ANTS swarm, collaborating to collect science data from the asteroid belt, is clearly inspired by nature and the biology of birds and bees, but exhibits enhancements over nature by virtue of techniques and approaches known to us from the fields of computing and engineering.

6 Conclusions

The human race has gained much from a greater understanding of biology. Understanding how the “program” of life works has made it possible to prevent many undesirable conditions, cure certain diseases and afflictions, devise new treatments and drugs and understand better when they can be used, etc.

Notwithstanding this greater understanding of biology, most of these advancements were due to the exploitation of modern computing technology and its application to biological problems, and in particular the ability to develop and explore (search) models of reality. We begin with such models, and enhance them with concepts not seen in nature or the real world [26], but deriving from advancements in computing and engineering.

Such modeling of biological phenomena and nature has enabled us to better understand the behavior patterns of insects, birds, and mammals. Simultaneously, an understanding of biology and nature has enabled the creation of a whole field of biologically-inspired computing. Ingenuity in nature has sparked imaginations and inspired ideas for means of developing complex computer systems that reduce complexity, enable the development of classes of system which we could never have achieved without this inspiration, and move towards self-governance of systems.

Biologically-inspired computing involves looking at biology and nature and models of it, and then adapting it and improving on it with advances made in computing technology and engineering.

Unlike Edison, at least in this context, we see the inspiration as being 99% of the effort, and believe that computing can benefit in many ways from biological inspiration. We believe that biologically-inspired computing should be 99% (biological) inspiration, combined with 1% mimicry.

> Look deep into nature, and you will understand everything better.
> *Albert Einstein (1879-1955)*

Acknowledgements

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Autonomic apoptosis was introduced in [14], and quiescence in [6]. More detailed expositions of the ANTS concept mission, and specifically the PAM submission, are given in [25,27, 28].

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