# Symbiotic Autonomous Systems
An FDC Initiative

## White Paper
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# Contents

# 1 Overview

This White Paper is the result of a joint effort by several people and represents a consensus reached among the members of the IEEE Symbiotic Autonomous Systems (SAS) Initiative at the end of October 2017. Since the SAS field is in continuous evolution, this White Paper should be considered a "work in progress."

SAS leverages many technologies and has applications in many vertical markets. The field will therefore have an increasing impact on our society—and on the way, each one of us perceives and relates to his or her environment. Hence, the issues related to Symbiotic Autonomous Systems go far beyond just technology evolution and utilization.

In this respect, the aims of this White Paper are to (1) highlight those issues that are clearly identifiable today, and (2) to indicate emerging issues, thus providing a starting point to those involved in making public policy to understand the technical fundamentals, their evolution and their potential implications.

The White Paper is structured as follows:

- **Evolution and Definition of Symbiotic Autonomous Systems**
  A general introduction to the area, touching upon the various aspects involved. It can be seen as an executive summary and may be of interest to the layperson.

- **Technology Evolution**
  An analysis of different sets of technologies applied to Sensors, Artificial Intelligence, Complex Systems Interactions, Communications and their trends in relation to the evolution of SAS.

- **Scenarios in Vertical Fields of Application**
  A number of scenarios that will also be recreated through digital mock-ups to allow a better understanding of the SAS implications in a variety of application fields, including education, health care, smart cities, industry 4.0, consumer electronics and augmented humans.

- **Ethical, Legal and Societal Implications**
  A first outline of the potential issues deriving from SAS as active, independent entities in society, including: socioeconomic impacts, technical ethical aspects, and technology-policy aspects.

- **Market Impact**
  A first glance onto the changes induced in the market, the shifts in the value chain and related perceptions of value plus some quantitative analyses in several verticals.

- **Further Notes on the Evolution of Machines and Humans**

- **Conclusion**

# 2 Evolution and Definition of Symbiotic Autonomous Systems

To a certain extent, human cultures have been characterized by the tools they made and used to the point where, starting with the Stone Age, these cultures are named after the predominance of a specific material used for tools. Notice that the idea of a tool is related to an artifact, more or less sophisticated but still manufactured by a human being to serve a specific purpose. The Stone Age was a time when our ancestors learned to shape stones in order to fit a specific purpose (to cut, drill, hit, scrape, etc.). Subsequent cultures have shown an increased capability to deal with additional materials (like bronze) in order to make new and more effective tools.

Tools as body extensions

Until the 18th century, tools were primarily an extension of our body powered by our muscles. While levers could trade displacement for strength, human power was limited by our muscle power (note that water/wind mills predated steam, but their application was constrained by the particular location).

With the invention and wide distribution of the steam engine, humanity quickly acquired the capability to use external power in ordinary fabrication methods. The issue for the culture of the 18th and 19th century became one of how to control this power.

At the end of the 19th century, electricity provided a new and different source of energy that was easier to control and use. As a consequence, electricity became the dominant way to manufacture products, including tools.

In the second part of the last century, the invention of computers made available a new *quality* of tools. Computer-controlled automated processes are improving the effectiveness of *control* and more recently have become outstanding tools for improving our reasoning and thinking capabilities.

Computers as tools for mind extension

We are in the Computer Age because many of our tools are directly or indirectly tied to computers. However, we are starting to see the emergence of a Digital Age in which the material to be manipulated and used for construction is no longer (just) atoms but also bits.

Spectacular advances in brain monitoring and in various forms of Brain-Computer Interface (BCI), including Deep Brain Stimulation (DBS), have definitely proved the unification of *soft* (thoughts) and *hard* (neurons and neuronal circuits) in the brain. At the same time, when considering SAS, this is creating new challenging questions about the emergence of shared thinking and shared awareness with profound ethical issues.

This digital technology evolution is moving us towards the availability of a seamless integration (at different levels) of these computer/digital tools with us, the users. These tools are becoming a seamless extension of our body and mind, as the hoe was an extension of the farmer's arm. This seamless integration is very important, because it implies that these new tools are fading from our consciousness, we take them for granted, and they become an integral part of our life.

Think about the many times we use our smartphones to "Google" a piece of information. When we do this, we are extending our brain's memory and knowledge using a prosthetic device without giving it a second thought.

The symbiotic relation with tools leads to humans 2.0

We are slowly entering into human 2.0 or, as some people have called it, transhumanism, and we are doing this through a symbiotic relation with our digital tools. These new tools have become complex entities that are probably better referred to as *systems*.

Actually, the proposed change of name, from tools to systems is the consequence of a new qualitative dimension of modern, computerized tools.

While today's computerized tools are far more complex than what was used just 100 years ago, this is not the most important factor. Rather, today's tools are starting to operate autonomously and without our direct intervention, thanks to a growing flexibility and an improved awareness of their environment and decision-making capabilities. They are operating to fulfil a goal and take what they consider are the required actions to pursue and achieve that goal. Clearly one point is *who* sets the goal - can it be set by the SAS itself, can the SAS change the goal on its own as the context changes and experience is gathered?

Never before in human history have we had tools with these characteristics. Robots are the first example of these types of tools that comes to mind. They come in many shapes and operate in different ways and for different purposes. They may differ significantly from each other, in terms of shape, dimension, functionality and cost. However, what matters most in the context of SAS is the varying degrees of autonomy they have, their capability to evolve (e.g., to learn and adapt), and their ability to interact with their environment, between themselves, and with humans.

Self-evolving, autonomous decision taking, advanced interaction capabilities

We are therefore interested in SAS because of these three aspects: autonomy, self-evolution and human interaction. As SAS developments continue to progress at an ever faster pace, they will change the landscape of manufacturing and life itself. They may even change what it means to be human.

Like all life on Earth, we have evolved to adapt our behavior to the context in which we live. However, by becoming able to change the environment to better suit our needs, humankind went a step further than simple adaptation. As a result, in the coming decades we will see that for the first time, artifacts that we have created will start to adapt themselves and their behavior based on their ecological context.

In short, we will be part of *their* context.

Hence, starting in the next decade and even more so in the further future, we will live in a dynamically changing world where we will be responding to the behavior of machines, machines will be responding to our behavior in a continuously changing fabric, and it will become progressively more difficult to distinguish between cause and effect between man and machine.

What is happening is the establishment of a symbiotic relation among (autonomous) systems as well as between them and humans.

There is yet another aspect of these trends that will become apparent over the next decade.

From symbiotic relation to emergence of new entities

The interaction of several systems, each one independent from the others but operating in a symbiotic relation with the others – humans included – will give rise to emergent entities that do not exist today. However, we are recognizing the abstract existence of something like a *smart city*, a *digital marketplace* or a *machine culture*. These entities are seemingly abstract concepts, although they are rooted in the interoperation of independent systems.

As an example, a smart city is the result of the interplay of several systems, including its citizens as a whole as well as individuals. We can design individual systems and even attempt to design a centralized control system for a complex set of systems, such as a city. However, a smart city cannot be designed in a top down way, as we would do with even a very complex system such as a manufacturing plant where everything is controlled. Just the simple fact that a city does not exist without its citizens and the impossibility of dealing or controlling each single citizen, as we would control a cog in a manufacturing plant, shows that conventional design approaches will not succeed.

In the past we felt that we could fully control a robot as we would a cog in a factory. However, as robots become more and more autonomous, aware and able to self-evolve, they will become increasingly similar to human citizens, thereby requiring different strategies for management and control.

This emergence of novel abstract (although very concrete) entities created by these complex interactions is probably the most momentous change we are going to face in the coming decades. To steer these trends in a direction that can maximize their usefulness and minimize their drawbacks requires novel approaches in design control and communications that for the first time will place our tools on the same level as ourselves.

A new area of science

The IEEE SAS Initiative in its first assessment is inclined to think that a new scientific branch, which we call Symbiotic Systems Science (SSS), rooted in the science of complex systems, taking into account the social and ethical implications, is required. Consequently, promoting studies in this area is one of the goals of the initiative.

SAS with human participation

The symbioses of artifacts with humans will move by little steps and has already begun. For example, prosthetic hands are becoming more and more sophisticated, and part of their increased functionality stems from the autonomous nature of the prosthetics. When we pick up an object, several control systems are at work, even though we are normally unaware of their operation. For example, we can effortlessly pick up a nut or a raspberry, and we know to modify the pressure for the nut versus the raspberry, which is easily crushed. The decision process involved is quite complex and it involves the cooperation of different systems; sensorial, touch, sight, motion, decision-making at the brain/cortical level, fine grading coordination by the cerebellum, immediate response by the spinal nodes, and more.

Prosthetic hands are now able to sense and interoperate with the person's neural system; they can also make local decisions (like the level of pressure to exercise). To a certain extent, these hands are *autonomous systems*, and they enter into a symbiotic relation with the person wearing them. Notice that this development is a continuously evolving process resulting in increasingly advanced symbiotic relationships currently involving evolution slanted towards the person who is (slowly) learning to adapt his or her actions and reactions to achieve a better control of the prosthetic. A leading edge prosthetic hand, different from the first model that did not have sophisticated interaction capability, would not fit a different person because over time a very specific symbiotic communication has evolved, mostly on the part of the person—today—but we are now seeing learning and adaptation taking place in the prosthetic hand as well.

Embedded Internet of Things (IoT) devices are also becoming more common (think of sensors to monitor chronic pathologies, smart drug dispensers like insulin pumps and home connected devices). IoT devices are getting more and more sophisticated. In a short while, these IoT products will communicate with each other through body area networks—and in the longer term, they are likely to create distributed decision points with an emergent intelligence. Shortly after this, a symbiotic relationship will be established with the person wearing the devices, first improving the person's well-being and then the user's physical performances and ultimately their intellectual performances as well. In this latter area, DBS and the progressively more sophisticated chips controlling it create a new way of interacting with the functioning of a person's brain, changing the way it works. This is the path leading to augmented humans, human 2.0 or transhumanism.

Augmented Humans, Humans 2.0, Transhumanism

Although these three terms are sometimes used interchangeably, we take the view of a progression where the first step is leading to augmenting the physical abilities of a person (imagine having a wavelength converter embedded in the eye that allow that person to see in the infrared or UV spectrum), then reaching a point where many persons are markedly different from "natural" people because of their extended capabilities. These could include specific "improvements" like a permanent, seamless, connection to the web, made possible by advanced BCIs. This stage would characterize the development of Human 2.0, and its main difference from augmenting the physical abilities of one person is the generalization that will involve many people.

Humans 2.0

While in the augmented human we are likely to see an evolution that starts (as it is already happening) to address some disabilities and then move on to provide augmented advanced functionality to very few people, in the development of human 2.0 we have a generalized adoption of the technology probably due to decreasing cost for implementation. (Note that it has been said that we are already at that stage because of the generalized and systematic use we make of the smartphone to pair the web to our brain-based memory.) What we have in mind with our interface with devices like our smart phones is not the full human 2.0. We might concede to call this Human 1.5 insofar as in the nearer future, human to machine interfaces will remain visible. The transition to Human 2.0 is marked by a seamless, often invisible, interface where you are not going to interact with the smartphone in an explicit way by typing or calling on Siri or Alexa but you simply think of something and related information pops up in your mind's eye after having been retrieved seamlessly from the web (or a local storage device that you may carry with you).

Augmented Humans

Transhumanism carried to the extremes may signal a transition to a new species not driven by evolution, but, rather, by technological development. Although transhumanism is rooted in the concept of leveraging science and technology, it is looking not at a symbiosis between us and our artifacts but to the possibility of changing, at a fundamental level, the characteristics (or some of them) of the human race.

Transhumanism

We think that artificts will evolve in a way that in some respects resembles the organic evolution of living creatures. The rapid development of technology enables this artifact evolution. It is therefore a natural step to extend the concept of symbioses one step farther applying it to the relation between artifacts as well as living creatures (like us).

Artifacts in a symbiotic relationship

Interestingly, we have examples in nature where these properties do not belong to individual components in a relationship but tend to emerge when many of these interact with one another as an ensemble. This is the case, for instance, for swarms of bees with a behavior as a group that is very different from that of individuals. Similarly, we can expect similar emergent behavior for swarms of robots. There is therefore a focus on two categories of symbiotic relationship only involving the interaction of artifacts with each other:

- Firstly, where each artifact demonstrates awareness-autonomy-evolution
- Secondly, where the ensemble demonstrates these properties as emerging property

In the former case, the symbiotic relationship may occur among only a few artifacts. An example is the area of robotics where as individual robots increase their awareness capabilities through better sensors and context data analyses, they become more and more autonomous with technologies supporting analyses and problem solving using AI/Deep Learning methods that evolves over time. This type of symbiotic relationship impacts several verticals—for example, Industry 4.0 (manufacturing and retail) and healthcare.

In the second type of symbiotic relationship, there is a need for a significant number of artifacts to create a symbiotic relationship with enough complexity that emergent behavior results. There are no defined thresholds for complexity above which these properties emerge, although in general the simpler the entities involved the more of them are required. We see this in nature where a flock of starlings gives rise to amazing choreography in the sky with hundreds of birds while in the case of a swarm of bees the number is in the order of several thousands.

These aggregations can be studied with the science of complexity along with other technologies in the domain of AI. These aggregations and their emerging properties will be a topic of growing interest in the domain of IoT, although very few studies have focused on that.

IoT and Big Data entering SAS domain

The interest derives from the fact that we are moving towards billions of IoT loosely connected with one another. AI technologies can use data from the devices to extract emerging properties and direct the behavior of the IoT in the cluster.

This completely new domain will come into play in the next decade, as the number of connected IoT will reach a threshold above which awareness-autonomy-evolution can take place. 5G is likely to be an enabling technology in this domain providing the communication fabric for the ever-smarter IoTs and clusters of IoTs.

The growing connectivity is an enabler of increasingly complex systems, provided that each (or several) of the various parts have some autonomous characteristics. In turn, the studying of various technologies and application areas will require the SAS view. Many of the IEEE Societies are likely to be affected, and one of the points raised by this White Paper is a call to action for several of them to include the SAS perspective in their work and foster cooperation amongst them.

A discussion and roadmap calling for joint action are outlined at the end of this White Paper.

# 3 Technology Evolution

There are several technologies playing a role in SAS, some complementary, some alternative. For the purpose of this White Paper, the technologies are grouped into the following functionality areas and categories:

*Advanced Interaction Capabilities*

- Sensor Technologies
- Actuator Technologies
- Communication Support Technologies
- Cooperative Support Technologies
- Augmented Human Technologies

*Self-Evolving Capabilities*

- Awareness Technologies and sentiment analyses
- (Machine) Learning Technologies
- Self-replication Technologies

*Autonomous Decision Taking Capabilities*

- Decision-Making Technologies
- Complex Systems Technologies
- Emergent Properties Technologies

The subdivision in functionality areas is made to help the reader focus on the outcome of a group of technologies, although in a few cases a given technology category is actually being used also in other functional areas. In this case, it will be referenced. Allocation has been decided by prevalence.

For each functional area a discussion on the expected evolution in sophistication, effectiveness and affordability is given by taking into account that a given functionality may be provided by a set of technologies and that where two technologies are alternative each would be able to support a given functionality. For each category a roadmap of the expected evolution and the potential stumbling blocks are presented.

Additionally, it should be noted that some basic technologies like processing, storage and power will keep evolving, enabling the growth of the ones that are specifically addressed here. In this White Paper their evolution is taken for granted in the sense that the demands posed on them by the other technologies being considered will be met by their evolution.

There will be periodical updates, as new technologies take the lead and current ones drift away from the expected path.

## 3.1 Advanced Interaction Capabilities

### 3.1.1 Sensor Technologies

Technologies for sensing the ambient environment have improved significantly and will continue to do so in the next decade. There is the possibility to "sense" electrical fields, acceleration, displacement, temperature, radiation, sounds, and force (including pressure, touch, and the presence of chemical compounds). Additionally, image capturing at high resolution and in low light condition is no longer a problem. In the area of "vision", significant progress is still being made in creating sensors that can detect objects and identify their relative position in a field of view. These are exploiting light field technologies and decrease significantly the processing required to "understand" what is in an image, something that is crucial for an autonomous system, like a self-driving car, but more generally in robotic vision.

Variety of sensors based on different technologies

The technologies adopted in sensors are based on mechanics, optics, electronics, and chemistry. In each area there has been impressive evolution, both in terms of performance (accuracy, sensitivity), dimension (miniaturization) and cost decrease. Sometimes this is achieved through software that can make up for hardware limitation, through signal processing and multiple sources sampling.

Smart materials with sensing capabilities

An interesting evolution, already in sight, is the embedding of sensing capability in materials (smart materials). The trend is towards using construction materials that have sensing capabilities as an integral part of their material structure, like concrete that can sense pressure and detect stress, rubber that can become a sort of skin detecting temperature and pressure (touch) variations, or material surfaces that detect the presence of light and its "quality." This evolution is of particular interest in robotics where smart materials can be used both as "skin" – detecting external conditions—and as muscles—detecting strength and position of the robot's parts.

Sensor networks

Another important evolution is the embedding of processing and communications capabilities in sensors. This enables some level of local signal processing and the creation of local sensor networks that integrate the data acquired and generate meaningful information (like a bridge detecting a "moving stress" on the structure and interpreting it as a heavy vehicle crossing it as opposed to a stress produced by a mudslide on one edge of the bridge). Sensor networks are becoming a crucial part of any autonomous systems since they can provide data that properly analyzed leads to context awareness.

Sensor and IoT evolution are correlated in that IoT technology often comprises ancillary and/or embedded sensors. This creates a volume of scale that will keep pushing performances, production efficiency and cost decreases in a virtual spiral that will accelerate innovations. There is no perceivable obstacle ahead, at least in the coming decade and this will greatly benefit autonomous systems.

Bio- based sensors

The direct or indirect use of living cells and their manipulation to acquire specific characteristics has led to the creation of sensors leveraging living material like bacteria and algae. As an example, blue-green algae are being used for sensing the presence of contaminants in marine and fresh water by measuring their density through fluorometers attuned to algae chlorophyll. Live cells have also been integrated in microfluidic devices to act as "bio-reporters" with the aim of enabling autonomous environment monitoring.

Bio- sensing

A slightly different situation applies to biosensors for interfacing with living beings. Here the evolution is also impressive but there is no silver bullet in sight. The sensing of activities occurring in a living being is complicated by several factors:

- the noise generated by concurrent, although unrelated activities (in the brain there is a flow of electrical/chemical activity related to, e.g., moving an arm that occurs in parallel with hundreds other electrical/chemical activities like seeing, hearing, regulating breathing)
- the distribution of signals over a broad area (staying with the example of moving an arm there are several parts and hundreds or thousands of neurons involved) makes it difficult to pick up the signals at the point of origin: the further away the signal is picked up the noisier it appears.
- the difficulty in keeping the sensing probe in place since the living matter is soft and keeps changing.
- the possible change in the way communications are generated and change in a living being (the process of learning changes the brain and in turns it changes the neurons involved in a given action/thought and their mutual communications).

Given the present state-of-the-art, it seems more likely that it will remain impossible to pinpoint the origin of single activities, and the evolution in this area is towards a global understanding of the semantics. Thus, the sensing will generate non-specific data and these will have to be processed to derive specific information.

Shifting sensing at semantic level

In a way, the approach is to mimic the human way of "understanding" another human, by observing the external behavior rather than by capturing what, internally, led to such behavior. Clearly, this approach works when the understanding can be derived from "actions" but it does not work when there is a need to capture thoughts (such as the case of creating a symbiotic relation with a paralyzed person who can only "think" about an action). In general, the approach of understanding through behavior observation is best for autonomous systems since it is unlikely that they can get a direct hook into another system. More on this is discussed in the Communications and Cooperative Support Technologies' sections.

### 3.1.2 Actuator Technologies

MEMS

Movement and its subsets (exercising pressure, shifting weight, and balance) have been accomplished through mechanical systems usually controlled by electronics. There are linear and rotary actuators, some using purely mechanical means while others use a mixture of mechanical and fluid power. Micro-movements have become possible using microelectromechanical systems (MEMS). Progress in coordination of movements has been significant; consider legged robots that can run, jump, avoid obstacles, and maintain equilibrium in difficult situations even when pushed.

Smart materials

More recently, the design of smart materials has made possible the construction of actuators working through the change of shape of a part by sending electrical signals to the material that result in a change in its structure. This is finding applications in many areas, notably in robot movements and prosthetics movements. Some smart materials have memory of their state so that once the electrical signal is removed they flip back to their original shape. These characteristics are also being used to create self-assembling systems.

Smart materials can dispose of the need for motors to create movement, within certain power boundaries, and this allows for more complex movement in a limited space. As an example, the implementation of movement of a prosthetic human hand requires roughly 30 degrees of freedom (30 different movements) and in turn, these would require in general 30 motors resulting in a bulky device that would not fit in a human-sized hand. By using smart materials to simulate actuation through synthetic muscles it is becoming possible to re-create the normal hand movement.

In case of micro power, studies are ongoing to use micro motors, as tiny as complex molecules. These may find application for drug delivery at the cell level or for microsurgery inside blood vessels. In perspective these may become rudimentary autonomous systems although within a very well defined ambient.

Optogenetics

In bio-interfaces optogenetics has become the leading technology. It is based on the introduction of specific gene/gene modification to make a cell responsive to a specific light wavelength, and by using optical fiber reaching the vicinity of the cell, it is possible to stimulate specific behavior at the cell level (usually neuron). The application of CRISPR/CAS9[1] technology may further improve optogenetics making it possible to tweak with genes directly without having to use a virus as a vector. At the same time this brings several ethical issues to the fore.

[1] CRISPR/CAS9 (Clustered Regularly Interspaced Short Palindromic Repeats/CRISPR associated protein 9) is a genome editing technology.

### 3.1.3 Communications Support Technologies

The increase in processing capacity has made possible the management of multiple communications channels. This is reaching a maturity with terminal devices (systems) able to manage a broad spectrum of frequencies at the same time and make autonomous decisions on which frequency to use. This management of frequencies will be leveraged in the next decade by 5G.

Internal and External Communications

Autonomous systems use both internal and external communications, and the advanced management of spectrum provides much more flexibility for these communications. In many instances, autonomous systems will keep their external communications activity to a minimum: since they are autonomous they will need the capability to be aware, understand their environment, and act in consequence without having to rely on what others are doing. This is at the root of autonomy. They will need to capture, or sense, what is going on and react accordingly. This sensing may be seen as a form of implicit communication. Likewise, their behavior or reaction to a changing environment is a sort of implicit communication towards other systems in their proximity. A car that is blinking its direction light is sending a message to whoever minds to take notice that it will soon turn in that direction.

Implicit versus Explicit Communications

Notice that in implicit communications there is no acknowledgement received, nor expected, although changes in the environment following an implicit communication may be indicating that the message was received and acted upon. The communications taking place in living organisms, among cells, are examples of implicit communications. For example, in the brain, there are many implicit communications (for example, all chemical changes such as serotonin levels). Discussion is still ongoing to determine if among neurons and neural circuits there is also explicit communications.

In explicit communications there are a number of parties involved, and they establish a "handshake" providing feedback on the reception and possibly further information to steer the evolution of behavior of the parties involved. Explicit communications do not characterize autonomous systems. However, explicit communication is and will be often used to increase the overall awareness and influences the behavior of each autonomous system.

Explicit Communications in autonomous systems

A crucial aspect related to explicit communications in autonomous systems is the demand for inherent flexibility of the communications structure, both at physical and logical level. In other words: with autonomous systems one cannot define *a priori* the communication rules (because one in general does not know with whom one will be communicating) but should rather provide a communications framework to support interactions among undefined parties. Within this communications framework there are some fixed, standardized, rules allowing the interacting partners to enter into a meaningful communication.

It is a bit like communications among human beings. Although we seldom notice, many communications take place in an implicit form. For example, as a person walks on a sidewalk and sees another person approaching, he will move slightly to the right (in most of Europe, however probably to the left in the UK!), and other person will do the same. All of this takes place naturally and without any explicit acknowledge. People communicating in the same language rely on common syntax and semantic to understand each other effectively. If, however, two people speak different languages, they may need to start the conversation by asking, "Do you speak English?" A positive answer would shift the communications framework to a specific set of rules. If the two people do not speak a common language, they may revert to a more limited communication mechanism such as gestures, pictures on paper and so on. It is not as good as sharing the rules provided by a spoken language but still it works. However, if one of the people in the conversation is deaf, voices will not work. The physical layer is not compatible; they will need to turn to a different physical layer, such as sign language.

The situation for explicit communications among autonomous systems is similar, from a conceptual viewpoint. First, there is the need of sharing a common physical layer; in the case of wireless communications, this means to use the same frequency. Wireless systems use a variety of frequencies because they provide a range of characteristics that can serve in different situations. Higher frequencies can potentially carry broader bandwidth but over shorter distances, while lower frequencies have better propagation characteristics but in general support less bandwidth (and are more crowded). There is a variety of standards for radio communications, and significant work remains to be done to leverage these standards in a situation where autonomous systems may need to interact with a variety of players with no a priori defined protocols.

Need for interoperable standards

WLAN communications (like IEEE 802.11) can present challenges indoor if the autonomous system has to roam in a large compound since propagation is limited by walls, particularly concrete walls. In this case, pervasive infrastructures (with beacons and repeaters) may be required. In cases where there is a multitude of autonomous systems, the communications fabric can be created autonomously. In the future this solution seems to be the most promising, given the increase in number in autonomous systems and more generally smart connected devices.

In case of autonomous vehicles, industry is at work to agree on standards both at the physical level (layer 1 frequencies) and transport layers 2-4. The increased capabilities of communications chips will support multiple frequencies so that an autonomous system will be able to communicate using a broad range of frequencies and agree with the other party or parties that one to use at a particular time. Industry 4.0 is another area where communications standards for autonomous systems are being developed.

### 3.1.4 Cooperative Support Technologies

Engineers have been building complex systems in which the various parts—implicitly and explicitly—cooperate with one another to achieve a desired goal or functionality. Design methodologies have been created to simplify the design of the various components and make sure they fit with one another and their overall interworking to achieve the desired behavior.

Action-driven vs goal-driven cooperation

Robots in a production line are cooperating with one another but the cooperation is actually a predefined set of individual goals (robot 1 moves the object 90° clockwise, robot 2 solders the object with a component that has to be taken from the moving beltway…). Hence we cannot talk, really, about two autonomous cooperating systems. They are not sharing a goal rather they are executing actions according to a predefined and bounded plan.

In the case of autonomous systems, different sorts of technologies are required in their design and thereafter in making cooperation possible and fruitful. Each autonomous system should be able to internalize a *global* goal and be aware of how that goal can be achieved through cooperation. An example[2] is thousands of micro robots that are given the goal of creating a shape by aggregating in some specific way that has to be determined by the robots themselves. There is no command to each specific robot to move in a certain position, rather a general instruction to create the shape of a circle, a square and so on. There are different approaches, from a technology point of view, and a lot of work remains to be done.

One approach is viable when each autonomous system has a significant processing and storage capability to the point of creating a virtual image of the overall context. This may be

[2] This example is taken from research carried out at the Wyss Institute, Harvard University, on self-organising robotic swarms. See references.

the case for self-driving cars that can cooperate to avoid unnecessary use of resources (finding the best way to go from point a to point b while avoiding clashes, i.e. creating traffic jams). Each car has its own virtual context and can share it with the other cars. Each context includes the specific goal for each car and an overall goal for all cars (avoid the creation of bottlenecks). By having an overall visibility and sharing the same overall goal each car will negotiate the next step with the other cars thus implementing the overall goal through cooperation.

Sharing a goal and cooperating to achieve it

A subset of this approach is characterized by the capability of autonomous systems to engage in a goal-orientated conversation to negotiate a set of actions to be performed in parallel or in a sequence to be jointly defined to achieve a goal. This is the approach followed, as an example, by Rethink Robotics[3] with Baxter, an autonomous robot designed with a human friendly interface supporting information exchange with humans in a collaborative framework (a clear step towards Industry 4.0 and beyond).

Cooperation through negotiations

A completely different approach is the one where each autonomous system participates to a multitude of similar systems (similar in the sense of subscribing to the same set of rules in analyzing the context). This is the sort of collaboration seen in swarms. Here the technologies required are the ones for modeling behavior of thousands and more interacting autonomous systems bound by strong and weak relations (with the latter usually being more important than the former) along the science of "small worlds." Interactions here are mostly with the context, not with a specific entity in the context. A change in an autonomous system behavior results in a contextual change perceived by other autonomous systems. This, in turn, will change their behavior accordingly. The set of these local changes results in a form of emergent cooperation.

Cooperation as emerging behaviour

The area of cooperative support technologies is in its infancy, and will progress significantly in the next decade as more and more autonomous systems will interact with one another.

### 3.1.5 Augmented Human Technologies

Humans have benefitted from several augmentation technologies over the centuries, from tools to increase their manipulation capabilities and their strength to devices to extend their senses, like microscopes and loudspeakers. This progress continues by providing augmentation that is more effective and that is becoming seamless, invisible and integrated in the human being.

Five main areas of augmentation technologies may be considered, but not limited to:

- Bionics
- Brain-Computer Interfaces
- Neurotechnologies
- Drugs and Nootropics
- Genetics

In this part of the document only the potential created by technology evolution is presented, the ethical aspects are considered in another section of the White Paper.

*Bionics*

Bionics can be seen as an evolution of prosthetics where the prosthetic has a deeper interaction with the human. A prosthetic leg (like the one of Peg-leg Pete) is a coarse make-do for a real leg, connected with some straps to the leg stub resulting from the partial limb

[3] Baxter has been designed to be able to learn by observing what humans do as well as to be taught by human co-workers by showing and coaching.

amputation). A bionic leg provides a replacement of the missed limb leveraging sophisticated technology that emulates real limb movement and interfaces with the body capturing electrical signals arriving at the muscles on the stump and in today's most sophisticated bionic leg, by providing electrical stimulus that can be interpreted by the brain as sensations. A computer inside the bionic leg analyzes signals from the body and from sensors in the prosthetic leg and recreates the appropriate movement to match the normal movement of that person. The goal is to have bionic prosthetics that can seamlessly integrate with the body.

Bionics go beyond Prosthetics

Technologies we view as the minimum required set at the core of bionics are:

- mathematical modelling
- sensors
- actuators
- signal processing
- smart materials
- Artificial Intelligence
- bio mechatronics
- 3D printing

The field of bionics has grown with the objective of helping people with an acquired deficit but is starting to look into augmentation of performances of normal people. As an example, military research in this area is clearly targeting augmentation of soldier performance, e.g., by using exoskeletons to help carrying loads and decrease fatigue.

From deficit care to augmentation

For example, glasses—a prosthesis long in use—have been evolving into a bionic device to augment vision, such as night goggles that allow visual perception of the infrared spectrum used by the military and rescue teams, as well as glasses that overlay digital information on the visual field: Advances such as Google Glass and Hololens have enhanced human visual perception through augmented reality, providing additional information in an almost seamless way. On the horizon are contact lenses able to overlay information (both text and images) on our line of sight, and further down the road are chips that can augment the retina capability. An initial use of these retinal devices will be to restore visual function to individuals with damaged retinas, an example being Argus II (Need reference or link)—but in the future they may be used for augmenting normal sight.

From wearable to embedded

Similarly, prosthetics for bettering aural perception are widespread, again aiming at restoring aural function although there are prosthetics to increase hearing sensitivity. In addition, here the trend is towards an integration of these bionic devices in the human body (cochlear implants are a first example). Haptic interfaces can increase the sense of touch and they are already being used by surgeons for microsurgery.

Augmentation can also take the form of providing new senses, like the possibility to detect magnetic or electrical fields as some animals have. Chips can be embedded under the skin to detect electrical fields and convert them into signals that can be perceived by the person. Through specific training the person can become able to detect these fields. Notice that this augmentation opens the door to increase communications capability. As an example, one could have a chip detecting Wi-Fi fields and decoding messages carried over Wi-Fi converting them into specific sensations. A guard can become aware of the presence of an intruder by receiving a radio signal that generates the sensation of "unwanted presence" felt like a twitching in a muscle in the left hand. Different level of twitching may mean the presence of one or several intruders. This potential military application may turn into a mass-market

Opening new sensory paths

application targeting shop keepers to let them know that a customer has entered the shop, or that a customer is standing still for a certain time looking at an object and may need help.

This form of augmentation is converting an incoming stream of data that would not be perceivable by our senses into one that can be perceived by transforming the media, i.e. a radio wave, into tactile nerve termination stimulation. Through training the person will be able to determine the meaning. This conversion sometimes occurs in the brain of a few people—synesthesia—where a sensation picked up from a sense, like an image from the eyes, is converted into a complex perception by the brain (as an example a person reading a series of numbers and feeling them as spatial points, or a person reading words and feeling colors in place of letter).

Bionics is going to become a main trend in the next and following decades. By the middle of this century, organ manufacturing will become common, and it is likely that these organs will be bionic ones, providing augmented features. Actually, bionics will progress to the point that some people might be tempted to exchange part of their body for a bionics replacement. Bionic add-ons will become widespread creating a strong business opportunity, although fraught with ethical issues.

*Brain-Computer Interfaces*

Biological brains—including ours—process sensory data arriving from biological sensors. The processing may result in the activation of parts of the body (like muscles to communicate or flee), or may just result in a change of state of the brain (e.g., memories and learning) explicit and implicit at a macro or micro level. The only possible way to get data into the brain was to stimulate the senses.

Better ways to look inside a brain

In the last fifty years—primarily in the last decade—researchers have found ways to read and directly stimulate the brain. This is the result of a growing understanding on the workings of the brain at the physical (electrical and chemical interactions among neurons) and architectural/functional level (neural circuits associated to specific processing activities). This has been made possible by technology evolution in the areas of:

- Neuroimaging (fMRI – functional Magnetic Resonance Imaging, PET – Positron Emission Tomography, CT – Computer Tomography, MEG – Magnetoencephalography, EEC – Electroencephalography, NIRS – Near Infrared Spectroscopy)
- Sensors array probes
- Signal processing (including Deep Learning)
- Optogenetics
- Neuromorphic Computing

Significant evolution is expected in the next and following decades both in the understanding of the brain circuitry and in the creation of seamless interfaces (this is part of the virtuous circle—better technology, better understanding, leading to better use of technology and further technology evolution). Today the more accurate reading of what is going on, the better the possibility to interface, and in turn this requires more cumbersome (and often invasive) physical interfaces.

As mentioned in the discussion of sensors evolution there is no silver bullet in sight also from a theoretical point of view: invasive probes, like sensor arrays, fail because of the reorganization taking place in the brain that would make any positioning useless over time since processing shifts from place to place and it is obviously impossible to trace each and every neuron activity.

A lot of hope is placed on signal processing to be able to filter interesting activity from noise or from irrelevant ones. To do this, however, a huge amount of data is required, and in turn this entails huge processing capability. Neuromorphic computing may be an interesting possibility to explore. At the same time, the collection of data remains tricky, even if one can insure accurate positioning of probes.

Invasive probes, although much more accurate, are not viable in the mass-market: only people with specific needs, like some forms of lock-in syndrome, would be eager to accept them. External probes, like electrodes on the skull, are more viable although much less informative.
Evolution is being driven by three classes of demand:

- Medical (for patients with various degrees of disabilities)
- Military (to maximize efficiency in communications)
- Gaming

As it has happened in other areas, military-driven evolution may affect the entire market, first in high-demand areas and then the mass-market.

The quest for a seamless BCI is likely to require new software approaches

BCI is an area where technology evolution is still dependent on scientific progress in brain understanding, and this is now actively pursued by The Human Brain Project funded by the EU and in the US by the National Institutes of Health-funded Brain Initiative, and by the Human Connectome.

Industry is also looking at BCI as something that is getting mature for generating business, and a few initiatives have been announced in the private sector, like Neuralink[4].

Industrial interest is growing

BCI can become an important means of communications in symbiotic autonomous systems involving humans but it is unlikely to happen in the next 20 years at a mass-market level. What can be expected is an adoption of more and more sophisticated technologies in the gaming area spilling off into entertainment and then into augmented reality areas. At that point, the step into more widespread adoption for interaction with a variety of systems, including appliances will be more a matter of cultural acceptance.

Clearly, the availability of a seamless BCI would make communications with the Internet and with devices much more effective. At the same time, it will create significant ethical and social issues, not to mention the rise of security concerns for potential hacking of the interface.

*Neurotechnologies*

The promise of a full understanding of the brain, made by projects like The Human Brain (EU) and The Brain Initiative, can potentially open the way to an augmentation of the brain processing and storage capabilities through the implant of chips that can improve memory and processing.

In this area, there is a fuzzy border between science and science fiction, and it will remain so for the next decade. Nevertheless, studies aiming at helping people with memory deficit are ongoing, and trials are being made with animals to improve the capability of remembering and storing experiences. Most focus on electrical or magnetic stimulation, through probes, of the hippocampus, which has been recognized to play a crucial role in forming long-term memories. Transcranial Magnetic Stimulation (TMS) technology has been tested[5] but the stimulation cannot reach the hippocampus and is limited to the external part of the brain (experiments have been taking place on the parietal cortex). Deep Brain Stimulation (DBS) is being tested

[4] Neuralink is an initiative launched by Elon Musk to develop commercially viable BCI in the coming years.
[5] Studies and trials have been carried out by Northwestern University

Chips for brain implants to augment memory and processing are now emerging with at least one having been demonstrated in limited human trials

as a potential help in Alzheimer's disease but it involves invasive surgery to place electrodes inside the brain.

Other trials are using weak electrical currents that can be focused on the hippocampus. A new technology using electrical pulses generated by several electrodes placed on the skull and timed in such a way that their propagation creates a strong pulse in a specific area of the brain is being proposed by MIT Center for Neurobiological Engineering as a way to create non-invasive hippocampus stimulation, and first tests are now being performed on humans. Hopefully, evolution in these technologies will affect the care of patients with memory disabilities and will contribute in understanding how memory works in the human brain potentially opening the way for memory augmentation through neurotechnologies. They may also serve as "memory backup[6]" in case of loss of memory due to trauma.

Although solutions are not in sight, issues related to brain augmentation through neurotechnologies are already being debated. Some, like Elon Musk, are even seeing this augmentation as a way to contrast the takeover by artificial intelligence once it will become "smarter" than humans. Others, like Bryan Johnson[7], are seeing this as a profound link between humans and their artifacts with a seamless continuum of natural intelligence and artificial intelligence. This will clearly be a situation of strong symbiotic relationship between a person and an artifact, the ambient.

It will also remain to be seen if placing a chip inside the brain for its augmentation would make more sense than the alternative establishment of a seamless connection between the brain and the internet where memory and processing can be tapped at will. In a way, it can be more an architectural issue of where to place the functionality. One could imagine an implanted chip that boosts one's memory and one's capability to speak/understand a foreign language or a seamless connection to the Internet via an implanted chip[8] transferring the voice (or text read) speaking to us, providing back the translation for our brain to process and then providing the translation of what we want to say by directing our speech to speak in the foreign language.

BCI versus neurotechnologies

For the time being, this latter implementation can fall into foreseeable technology feasibility, the former is still in the boundary of science fiction. Of course, variations to this situation can already be feasible with a microphone picking up the voice at the same time of our ears, providing the translation through text (augmented reality) or an earbud, listening to what we say in our language as reply, and providing a real time translation. This in a way is also augmenting our capability, although it is not augmenting our brain directly.

The implantation of a chip in the brain, apart from its feasibility in terms of memory and processing augmentation, is also raising issues on how the brain in the long term will react to this. Under the assumption that it might be feasible and seamless from the point of view of brain thought processes, how will the brain change/evolve in consequence of this booster? Our brain is continually evolving as result of newly acquired capabilities (learning), and in principle, this should be the case for a seamless chip implant.

Augmentation through technology remains a double-edged sword, and it will be so for brain augmentation, although it is impossible now to understand fully its implications.

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[6] DARPA is funding a project to create a brain implant that could store memories as they are gathered and restore them in case of traumatic loss.
[7] According to Bryan Johnson, one of the funder of Kernel (https://kernel.co), "The relationship between human intelligence and artificial intelligence (HI + AI) will necessarily be one of symbiosis. The challenge and potential of exploring this co-evolutionary future is the biggest story of the next century"
[8] DARPA is funding with S65 million $the development of neural implants to create a seamless connection between a brain and a computer.

*Drugs and Nootropics*

Augmentation of humans has been achieved in the last 100 years and has been accelerating in the last decades, through the use of drugs. Antibiotics have changed the outcome of bacterial diseases and have significantly extended life expectancy. Purification of water has probably been the most significant factor in decreasing children mortality. Fertilizers and insecticides have boosted agriculture and food availability to billions of people resulting in better nourishment and in life extensions. Although seldom considered when talking about human augmentation, all these factors have greatly improved human condition, extended our life span and evolved our species to be more resilient, stronger (taller!) and, indirectly, smarter (because of the increased wealth and time available that can both foster education).

Augmentation through drugs has been happening for some time

Augmentation through better drugs, both for us and for the environment, resulting in a better ambient will continue in the coming decades.

More specific drugs have been created to augment human performance, like the ones to increase muscle mass (steroids). They have been so effective that bans have been imposed to avoid unfair advantage in sporting competition. Bans have also been imposed because some of these drugs have shown undesired effects on the health of the person. It may be expected that more drugs will be created in the coming years to improve physical capabilities (including fatigue endurance), and that ways will be found to decrease (or even nullify) undesired effects.

Research has gone beyond the creation of drugs for augmenting physical performances, stepping into the area of emotional improvement (drugs fighting depression), alertness (caffeine is an obvious example but there are a variety of drugs like amphetamines that lead to undesired effects) and sharper thinking. Brain processing depends on electrical transmission among neurons and on the chemical environment around the neurons. Both can be influenced by drugs. Hallucinogens are a clear example of how drugs can influence the processing of the brain, altering sensations and thoughts.

From physical performance to emotional and thought augmentation

In the last decades a number of specific drugs have been found to "augment" the processing capacity of the brain, although studies are insufficient both in verifying their efficacy and, more important, in assessing side effects. Caffeine, as mentioned, has been known, also empirically, to increase alertness and in some way to make the person feeling sharp (how much sharper is yet to be demonstrated); however, it is also known that caffeine has some drawbacks, leaving a sense of fatigue once its alertness effects fades, and continuing to drink coffee to replenish the caffeine content in the body is not advisable.

In general, it seems that what a drug can offer in terms of making a brain "smarter" will be taken back once the effect fades away. However, there is the possibility that new drugs may indeed improve brain function, thereby augmenting its thinking capability. These drugs are known as "nootropics", and researchers are at work to find them.

The general issues with nootropics are that it is extremely difficult to target specific neural circuits, and their effects are pervasive. This is also the case for natural chemicals produced by the brain, like serotonin: they affect the whole brain, not just one part although their effects may be more visible in relation to a specific aspect (like mood change or loss of sleep).

Nootropic drugs

Compounds like cholinergic and racetams have been shown to have brain enhancement properties and are part of the nootropic family.  There is too little scientific and clinical testing so far to take a stand but given the complexity of the brain in terms of finely balanced environment extreme caution is advised by medical doctors.

It is clear, however, that nootropics will evolve, also thanks to better understanding of the brain and to the possibility of closer monitoring the effects of these substances, and they will play a role in brain augmentation in the future decades. Implanted brain dispensers may provide both the right dose and the best delivery place and ensure the monitoring for a continuous precise and customized dosage. This may happen in the fourth decade in this century (since it will be dependent of the maturation of brain implant technology). The implants may be required not just because of the problems in crossing the blood brain barrier that is stopping most substances from affecting the brain but also allowing a more targeted delivery. Delivery may be synchronized with the rise of specific needs, and this synchronization may be the effect of interaction with other autonomous systems leading to a truly symbiotic relation.

Brain implants as nootropic drugs dispensers

*Genetics*

Possibly the ultimate technology for augmentation could be genetic manipulation. Clearly this is also the one that brings to the fore most ethical issues and concern.

Genetic manipulation has become easier with the CRISPR/Cas 9 technology and laboratory procedures are now becoming standardized and economically affordable to scale up. Because of this there could be no doubt that sometime, somewhere, the genetic manipulation that is now common bacteria, plants and some animals will overflow into humans in what is called human genetic engineering. The first steps have already been taken with experiments in China on human's embryos, and discussion is raging in many countries no longer on the ban or permission but on the boundaries.

CRISPR/Cas9

Germinal choice technology, another name for reprogenetic technologies—the ones looking at human reproduction—are already being considered as a way to avoid genetic disorders by tweaking the genes before fertilizing the egg. Experiments on mice have shown that through genetic manipulation it is possible to create species that live longer and even extend the life span to a mouse by working on the telomeres.

Reprogenetic technologies

The possibility offered by an ever growing genome data base, now already populated with hundreds of thousands of genomes, a number to grow fast into millions in the next few years, to compare genomes and identify "problematic" genes associated to a variety of syndromes or predisposing a person to certain pathologies will boost the interest to edit the genome, both at fertilization time and after as a way to cure or contain symptoms.

Leveraging Big Data in genomics

These interventions, motivated by avoiding or recovering from undesired pathologies, are likely to be culturally accepted and approved by regulatory bodies since they are considered nothing more than a different "medicine" (more effective and sometimes the only cure).

Genetics as a cure

A different story is the use of genetics to augment the human being. Here, as well, there are a lot of grey areas, like the possibility of extending human life that culturally may not be seen as "bad" although it brings social and economic issues (in addition to the aspects of different degrees of affordability that will create gaps in the society). What about the possibilities of augmenting resistance to fatigue, or improving muscle strength[9]?

Genetics for augmentation

[9] A genetic modification that occurs in a few cases, involving myostatin gene deletion, leading to increased strength

By observing the overall gene pool and identifying those combinations resulting in a more performant human it would be possible to extend those combinations to future generations thus augmenting their capabilities, both in physical and thinking performance. In some cases, it will be like moving artificial intelligence to the brain. In this scenario one could claim that it would not be about modifying the human species, rather giving the advantage of selection to many more. This, however, suspiciously resembles the selection nightmares of the past, just achieved in a more effective way (and therefore even more worrisome).

It should be noted that human augmentation through genetics could also happen through the modification of bacterial genes. Our bodies are populated by bacteria living in a symbiotic relationship. There are ten times as many microbial cells in our body as there are our own cells. Some of these microbial cells are essential to our life. In addition, some of these microbial cells, in principle might be modified to augment human capabilities. As an example one could modify symbiotic bacterial living in our gut to have them process cellulose (as if it happens for cows). That would give that human the possibility to eat cellulose, expanding his nourishment capability. Indeed, this might be seen as a solution to a growing population and quest for food. Although this gene manipulation may seem to raise fewer ethical concerns, it would still lead into unexpected surprises.

Bacterial genetic modification for human augmentation

Indeed, the tweaking with the gene pool can obviously lead to an unexplored path, moving into areas where natural selection never went, or if it did it backtracked since they are not existent now. The whole area of genetics, as soon as it shifts from the goal of curing disease (including avoiding genetic diseases) is fraught with concerns. Moreover, for some, even limiting it to curing disease is difficult to accept. Nevertheless, technologies are evolving in this area as well, maybe even faster than in other areas and need to be considered at a social, cultural and ethical level.

## 3.2 Self-Evolving Capabilities

### 3.2.1 Awareness Technologies, Intention Recognition, and Sentiment Analyses

Autonomous systems need to have situational awareness; that is, they need to be aware of their surroundings and aware of their possible evolution. An autonomous vehicle needs to identify the objects in its surrounding and understand their characteristics: a bench on a sidewalk and a light pole are not going to move around, but the boy sitting on the bench may move and jump into the street suddenly especially if he is bouncing a ball, however if the boy has a cast on his leg his possible movements will be much slower. Context awareness requires the ability to predict what may happen even if there are no immediate signs. As an example, an autonomous vehicle approaching a blind crossing cannot detect any incoming vehicles, but needs to be aware that there might be incoming vehicles—but if there is visibility and no other vehicle nearby, then there will be no vehicles contending the crossing.

Context awareness: What is going on? What could happen?

Autonomous systems acquire a "personality": sentiment analyses

The above examples make clear the complexity faced by awareness technologies and how, sometimes—particularly when confronted with living organisms, like humans, dogs, cats, and so on—they need to enter into the sentiment analyses, imagining a sentient being's intention.

Interestingly, in a world populated by autonomous systems sentiment analysis shall be applied to them as well. Not all autonomous systems will be alike, each one will have its own character and predisposition to act in a certain way and this may change depending on the situation and over time, just like a sentient being. Actually, the more sophisticated the autonomous system the more likely the need for some sort of sentiment analyses. This is a new area of science that will need to be developed. From the point of view of an autonomous system, every object has to be looked upon with some sort of suspicion, in a way of saying, about its possible behavior.

These technologies are based on computer vision and its sub areas of image processing, image analyses, machine vision and pattern recognition. The challenges are quite similar to the ones faced by living organisms. Visual processing of living organisms and the subsequent decision taking strategies are areas of current and ongoing research. Out of these studies, usually under the label of neurobiology, the scientific branches of neural nets and deep learning have emerged. The study of biological vision therefore invokes studies of consciousness and their relation to the interpretation of visual stimuli and decision taking processes.

Learning from living organisms' awareness processes

Sensors are usually providing 2D images and these images need to be converted into 3D models. Some sensors can provide information on depth, thus helping in singling out objects in an image. Analyses of colors can determine differences in hues from shadows, and shadows can help in gauging distances. Notice the importance of context and experience in extracting meaning from shadows. Our brain processes shadows assuming light comes from above. Under this assumption it detects *bas-relief* versus engravings. By changing the direction of light it is possible to trick our brain in seeing as *bas-relief* what is actually an engraving and vice versa. These types of phenomena challenge image recognition algorithms that first need to determine the direction of the light illuminating the subject. In the case of machine vision, this can be active or passive (i.e., the illuminating light can be machine-generated ambient).

A growing area of interest is the exploitation of communications among autonomous systems to create a global awareness. Autonomous vehicles may interact with one another to get a global understanding. Military applications are fast advancing on this approach, for example, the creation of swarm awareness using drones that can collaborate to identify objects, understand what is going on, and then know what to do.

Awareness through cooperation

In general, one can identify three technology areas in situation awareness: perception, comprehension, and planning. These areas are pursued, as much as possible in a loosely collaborative way, where "loosely" reflects the nature of autonomy since each autonomous system, by definition, can exist and operate in isolation.

Also, one should notice that in cases where one of the autonomous system is a living being, like a human driver in a self-driving car, a symbiotic autonomous relationship emerges and has to be taken into consideration. Studies are already underway on these symbiotic relationships and many more are needed. As more self-driving cars will take the road more experience will be gained on these relations from the field.

Awareness in symbiotic autonomous systems

In general, there will be a shift of paradigm from the centrality of the driver (the car should not distract the driver, hence essential interfaces conducive to focus attention on the road) to partial automation, that is functions that are taken away from the driver (stability control, braking control) executed through technologies that the driver no longer needs to know. As trust builds up from the driver side, the risk is one of less attention being paid and more time required if intervention becomes necessary.

In the future, there will be partial automation all of the time or full automation part of the time (e.g., self-parking, highway driving). Here the issues are about understanding the shared responsibilities and the capability to take over (both ways—by the human driver and by the car).

Fulltime car automation completes the paradigm change from attention being the key issue for the driver to situation awareness being the key issue for the car. Notice that in the case of the driver, situation awareness is a given provided the driver pays attention (this is not always true; as an example an intoxicated driver may pay attention but no longer be situation-aware).

Evolving relationship between a driver and her self-driving car

In case of a symbiotic driver/car relationship, the car that is becoming situationally aware should identify if there is something the driver should worry about (e.g. a malfunction, running short on gas). This shift is likely to transition the driver from paying attention to "not wanting to pay attention" and being engaged in other activities, and this needs to be taken into account in a symbiotic relation. This trend is already emerging, with NVIDIA announcing the first in-vehicle computer designed to run Level 5 Autonomy self-driving vehicles (no pedals, no steering wheel, and no need for anyone to ever take control). This essential component of a fully vehicle/human SAS will be released in 2018.

These set of issues are already faced by today's commercial flight pilots that trust the automated flight control and because of that can lose situation awareness. This creates significant challenges in situations that are not "in the book."

Sentiment analyses, mood detection, and empathic engagement are on the horizon of autonomous systems requirements list. Technologies that are based on artificial intelligence algorithms can focus on a single person as well as on a group of people (as large as a community or a citizenship in a town). There are several APIs available to detect mood[10] based on face image on videos, speech and text (with these latter involving semantic analyses).

Sentiment analyses and mood detection

In the future, a sort of sentiment analyses will be required to infer the "character" of an autonomous system once a need for interaction arises. This will be used to fine-tune an interaction framework from need-to-cooperate to willingness-to-cooperate to symbiotic cooperation.

In the future, symbiotic autonomous systems operating in health care will be facing situation awareness issues. Embedded medical devices will benefit from interaction among them to get overall situation awareness.

*Phatic technologies*

Technologies supporting situation awareness will also have an impact in the area of phatic technologies, the technologies used by humans to set up, maintain and reinforce a relationship (among humans); clearly they involve communications. As boundaries of interactions among humans and machines are getting blurred phatic technologies will be applied to the symbiotic relations across humans and machines.

Autonomous systems entering the area of social groups

The Internet has been the source of a strong evolution, with social networks, social media and social communications that have expanded the possibility of setting up, reinforcing and maintain group relationships. We are already starting to see groups moderated by machine (initially for "policing" purposes), and we have virtual machines that play the role of a journalist sorting content and creating ad hoc publications fitting a specific group of interest. They are now evolving with the possibility of managing interaction, responding to questions, setting up discussion areas and so on.

[10] Technology evolution is driven by a growing demand for emotion detection stemming by the business needs to better understand clients and evaluate the most effective ways of interaction. The market is expected to grow from the 2,.77B$ of 2015 to the 6.19B$ in 2020.
http://www.marketsandmarkets.com/Market-Reports/facial-recognition-market-995.html

Although for many years a need for socialization among autonomous systems is unlikely it is not unreasonable to think that phatic technology will be needed to support symbiotic autonomous systems relations, wherever humans are involved.

### 3.2.2 (Machine) Learning Technologies

Learning technologies have been focusing on human beings and how to improve human learning. Significant advances have been made in the last decades leveraging computer and Internet power compounded with the availability of more and more flexible and ubiquitous devices. This evolution will continue as more understanding on learning processes in the brain becomes available and more effective technologies for gathering, communicating, rendering, and personalizing information become affordable[11].

Processing and storage evolution push machine learning evolution

At the same time, machine learning is progressing rapidly, thanks to more processing power and more storage availability in machines, in addition to the possibility to leverage the experiences of thousands of machines in the cloud.

Autonomous systems can greatly benefit from embedded learning capabilities and from learning from each other and as a community. This machine learning tends to merge into the human learning given the overlapping of several aspects, although clear difference exists (today making learning easier for humans but the balance is rapidly shifting to the machines).

Explicit vs Implicit Knowledge

Learning has, for eons, implied access to something, somebody, who owns the knowledge and that was willing to share it in a way that could be learned." One way of sharing, of course, is to write down the knowledge in a book and have others read the book. This goes for explicit knowledge and we can see this kind of knowledge (easily) passed on to an autonomous system by *uploading* it to its "brain" (extending its database, its programming capabilities). There is another kind of knowledge, implicit knowledge (e.g., riding a bicycle), that cannot be coded into a book. Learning to ride a bike cannot occur by reading a book, regardless of how precisely the book has been written. Only through experience, failure, and further attempts can implicit knowledge be learned.

Leveraging on experience

This kind of learning is possible for autonomous systems that can be programmed to experience and improve (learn). Walking robots can learn to walk better and to walk on rough terrain by experience. Roomba learns about its environment by exploring it as it does its vacuum cleaning chores.
There is also learning that requires the "building" of knowledge. Research is an example; finding the demonstration to a new theorem is another example.

Learning through knowledge creation

Autonomous systems, equipped with deep learning technology, are able to explore new ways and create knowledge faster than humans. We have software that can demonstrate theorems that have not been demonstrated before and software that can play a game (like Go) creating new strategies that it has not "learned" from any book (or observing any other entity doing it).

An autonomous system "brain" can learn by "arguing" with itself, as AlphaGo did to get better at Go. It started with the "normal" learning process, by looking at what good players do[12],

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[11] Research is going on looking at the possibility of augmenting brain learning capability by tweaking with the brain, as an example through electrical stimulation of the hippocampus or elevating magnesium levels in the brain.

[12] AlphaGo neural networks were trained on over 30 million moves actually made by Go players, becoming able to predict with a 57% accuracy the move a player would execute. This is also an interesting capability for an autonomous system: predicting what may happen next. Then it started

then it started to play thousands of games against itself learning from their outcome and getting smarter and smarter through a process of "deep reinforced learning."

The possibility for an autonomous system to "autonomously" learn opens up the issue of losing control on the system itself, i.e. the system may learn and therefore act in ways that have been neither designed nor envisaged.

Collective Learning

Collective learning (also called *ensemble learning*) is becoming increasingly common. It is already a reality with Tesla cars. The autopilot system on a Tesla car has been programmed to learn as it gets more and more experience. In addition, since 2016, each Tesla car reports on a daily bases its "experience" and this creates a collective experience that greatly increases the learning speed of each car. The collective experience is processed centrally and emerging "lessons" are then distributed to all cars. It is like each car, every day, would drive over 1 million miles[13], clearly harvesting a huge experience.

According to Gartner Hype Cycle 2017, there are hosts of autonomous systems learning technologies that are established and experimental, and that are contributing to this area, including[14]:

*Hitting the market*
- Ensemble learning
- Convolutional networks
- Video Image analytics (learning from image analyses)
- Simulation

*Peak of expectation*
- Deep learning
- Cognitive computing
- Prescriptive analytics
- Augmented data discovery
- Graph analytics
- Predictive analyses
- Data lakes

*On the rise*
- Human in the loop crowdsourcing
- Artificial general intelligence
- Conversational analytics
- Embedded analytics
- IoT Edge analytics
- Advanced anomaly detection
- Citizen data science

Notice that among the technologies on the rise, "human in the loop crowdsourcing" directly relates to the learning of symbiotic autonomous systems.

### 3.2.3 Self-replication Technologies

Life is, by definition, a self-replication technology. From viruses and bacteria to complex organisms, each form of life exists because it has found a way to replicate itself (and in this

playing thousands of games against itself trying new strategies and reinforcing the ones that proved successful.

[13] The Tesla "fleet" is driving every day over 1.6 million miles. Clearly several cars are driving along the same road. Still, they are driving it at different times so they will acquire different experiences.

[14] The list and its classification takes into account, modifies and expands the Garter Hype Cycle 2017 report on Data Science and Machine Learning.

process to get fitter with its environment). Inanimate objects, like artifacts, do not have the capability to replicate themselves. The differentiation between a living organism and an object gets fuzzier as we approach a molecular level. Here the difference between a virus and a complex molecule, like a protein, is not overwhelming. Indeed, as viruses have to leverage on the external ambient (a cell, a bacteria) to replicate so a protein needs to leverage on an external mechanism to replicate. This is what happens repeatedly in our cells.

Here the point is not to discuss if a protein may be considered as "alive" or not, rather if the same mechanisms that lead to a protein replication may be applied to more complex objects leading to replication capabilities[15]. At the molecular level, researchers have already created replicating strings of DNA, and this has led to replicating DNA computers, as an example. The whole sequencing of the genome is an example of replication at work.

Smart materials are being studied to offer replication capabilities. Robots have been designed since last decade and significant work in this area is steered by space exploration where self-replication is considered very important. Work at Cornell University on replicating robots made by cubes that can self-assemble is pointing out to the rise of a new science that of self-replication, based on the measure of the level of information replicated. If one were able to replicate 100% of the information (cloning) then one would have replicated completely, however this is not necessarily what is needed/wanted. As an example, a robot replicating itself may want to maintain its identity and create a robot that is almost like itself but with a different identity.

The rise of a new science: self-replication

Notice that self-replication does not imply the capability to harvest the materials required for the replication. Clearly, a supply of that material should be available but this can be provided by a third party (as it is the case for living beings that often work in a symbiotic relationship with other to become self-sustainable).

The acknowledgment that self-replication may lead to a new being that is not 100% equal to the original one, opens up the point of evolution through replication as it has happened to life on Earth. However, it should be noted that evolution as we know it, has required eons and a multitude of random variations, which is not the case for a self-replicating machine. Here evolution can happen through replication by design, and indeed researchers are working to capitalize on the experience of a machine to improve its self-generated offspring.

The need for an adequate supply chain to fuel a self-replicating machine is also limiting the replication: in general, the more complex the replicating organisms are, the more time is required for the replication taking into account the need to create and maintain an adequate supply chain.

Evolution through Replication

So far this discussion has taken as a given that the machines are made of atoms. Actually, there is a new class of machines, made of bits, that need to be considered, and for these, the replication takes on a different flavor and is subject to much less constraints. Cloning of software in the sense of activating several instances of an application is normal and is not considered to be replication. On the other hand, the creation of software bots that can replicate and roam the web *is* a form of replication. (Soft-bots refer to robots made of atoms, using silicone like substances making them soft, and these fall under the previous category of atom based bots)[16]

Today software bots are based on weak AI, in the sense that they can be very smart but in some very narrow endeavor. DeepMind AlphaGo has proven to be extremely good at playing Go (hence very smart, smarter than the human world champion)—but that is basically it. You cannot converse with AlphaGo as you

Weak vs Strong AI

[15] Notice, however, that this creates the ethical issue of deciding if a self-replicating machine should be considered or not.
[16] http://cba.mit.edu

would with your friend and not even with Siri (which is another software bot specialized in another area). Work is going on to reach strong AI (also referred to as Artificial General Intelligence), an artificial intelligence that for its breadth compares to human intelligence. Technology is not close to reaching strong AI, and once reached its implementation at the level of software bots is not a given.

An area of research is the intelligence of swarms, and within swarms it is easier to envisage self-replication in individual components of the swarm. The collective intelligence can actually steer towards the replication of some/all of the swarm components. Interestingly, self-replication technologies are creating new legal issues. Manipulation of the genome to obtain crops with specific characteristics is protected by law (the genetic modification can be patented). The issue is what happens to the second generation of crop; here opinions diverge[17]. Even if ruling for crops can go one way, the ruling over software bots or replicating robots that may change, evolve, may be different. It is a new area of study, beyond technology.

Swarm Intelligence

*Dynamic Brain Emulation: Mind Uploading & Substrate-Independent Minds*

When applied to complex macroscale biological lifeforms, the term self-replication typically refers to somatic cloning. However, the longer-term penultimate cloning challenge is the replication not of the human body, but rather of the human mind, in the early-stage, a primarily theoretical endeavor often referred to in science, technology-focused Transhumanism as *Dynamic Brain Emulation* or *mind uploading*, referred to hereafter as DBE. (Note that in a non-dualistic definition of the so-called mind-body problem, the *mind* can be viewed as an emergent experience of the activity of our brain's highly-interdigitated neural activity patterns and neuronal interconnectivity —that is, our functional and structural connectomes, respectively—that form the physical foundation of both our species-wide cognitive capabilities and individually-specific personalities.)

Dynamic Brain Emulation | Mind Uploading

There are two DBE schools of thought, these being techniques that are either neurally non-destructive or neurally destructive. This section will focus only on non-destructive technologies that discuss various proposed processes of scanning an individual's brain to capture and replicate memories, personality, and all other specific attributes by transference to, in principal, any compatible biological, technological or integrated biomorphic technological platform – possibly including such unlikely substrates as water- and slime mold-based logic circuits – each referred to as a *Substrate-Independent Mind* (SIM). If the *self* is defined as being equivalent to the mind – and with some resulting controversy – DBE thereby appears to offer (1) a form of technological immortality, and (2) the possibility of one individual mind being transferred into multiple simultaneous selves.

Neural scanning and data acquisition technologies

DBE technologies are in various stages of R&D, these ranging from proposal and design to prototype and experimental application. The following three examples articulate the wide diversity in potential DBE technology already in development and testing.

- **Neural dust:** Scalable (10–100 μm) free-floating, independent battery-free sensor motes partnered with a sub cranial wireless ultrasonic backscatter[18] transducer that alternates between powering the device and transmitting a series of pulses that detect reflected modulated electrophysiological signals. Moreover, the transducer provides long-range communications, allowing the neural dust motes to function as a brain-machine interface (BMI) with lifelong operational capacity that, when implanted in sufficient numbers, could potentially serve to perform DBE scanning. Neural dust

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[17] Monsanto won a ruling of the Supreme Court in 2013, enforcing its rights on modified seed (soya beans) even after self-replication.
[18] Ambient backscatter communications transmit data without a power source by using ambient RF signals.

prototypes (a piezoelectric crystal, a single custom transistor, and a pair of recording electrodes assembled on a flexible PCB) viability has been experimentally validated both *in vitro* and *in vivo*, the latter by successfully reporting both electroneurogram (ENG) recordings from the sciatic nerve and electromyography (EMG) recordings from the gastrocnemius muscle in the rat peripheral nervous system and skeletal muscle, respectively.

- **Injectable mesh electronics:** An ultra-flexible open mesh implant injected into the brain via a syringe, injectable mesh electronic probes have a neuromorphic structure (i.e., similar to neural tissue) and are the same size or smaller than neurons. These characteristics provide several unique advantages when compared to conventional probes: a minimal neural tissue immune response, resulting in no post implantation inflammation or scarring; a seamless interface with brain tissue, allowing the mesh probe and neural tissue to structurally interdigitate; no requirement for a power supply by directly recordings neural voltage changes; the ability to interface with all regions and levels of the brain from single neurons through neural circuits and entire neural networks; and the possibility of never requiring removal. In addition, injectable open mesh technology will allow chronic *in vivo* recording and modulation of brain activity, and thereby is a potential candidate for DBE scanning.

- **Neurotropic viruses:** Neurotropic viruses (those with an affinity for neural tissue) follow neural pathways, which give them exceptional utility in articulating neural circuits. This is particularly helpful in visualizing axonal transport in tracing both anterograde (from soma to synapse) and retrograde (from synapse to soma) neural connectivity, and thereby neuroanatomy. (Neurotropic viruses and strains vary in their preference for traversing anterograde or retrograde tracing of neural projections.) Moreover, genetic viral modifications have resulted in a range of refinements and enhancements, including synaptic spread control and the incorporation of marker genes. Finally, the utility of neurotropic viruses in elucidating neuronal projections has been demonstrated *in vitro* and *in vivo*, suggesting that the technology could be a potential DBE scanning technique.

In addition to the symbiosis of neurobiology and replicated substrate, as well as the autonomous functionality of the DBE neural scanning technologies described, it is the earlier-mentioned potential for coexistent replicated selves that evokes the most salient aspect of DBE being classified as an SAS technology: If each of any given two or more multiple SIMs (or *cognitive replicants*) based on a single individual's DBE replication transfer are to maintain the same identity despite having unique experiences, they must be symbiotically linked such that that while autonomous they remain synchronized in as near to real-time as possible. Note as well that while the literature also describes the alternative scenario—i.e., that the various cognitive replicants diverge from the point of transfer, thereby evolving in a manner analogous to identical biological twins—these divergent cognitive replicants retain a significant symbiosis while evolving within an autonomous context.

Multiple linked cognitive replicants

## 3.3 Autonomous Decisional Capabilities

### 3.3.1 Decision-making Technologies

A crucial aspect for autonomous systems, be it a drone, a manufacturing robot, or a self-driving car, is the ability to make decisions in real time. Notice that the decision-making capability is actually a variety of degrees from a fully controlled system (from a third party taking full responsibility and leaving just the implementation to the system) to full decision-making by the autonomous system.

Variety of degrees in decision-making autonomy

In the case of a "human in the loop", we can see the human making all decisions, the human becoming part of the system, or the human being one of the interacting systems each one making its own decision (influencing and being influenced by other systems decisions). As an example, until the end of last century the pilot made the decision on deploying flaps, and the aircraft would execute those decisions. Beginning with this century, the aircraft aerodynamics has become so sophisticated that the tiny variations to the wings' geometry can no longer be decided by the pilot, and it is the aircraft that makes the decision based on inputs from the pilot (like altitude, speed, climbing rate) and from sensors (like the pitot tube measuring airspeed). The pilot has become part of the system. In the future, the geometry of the wing will be the result of several interacting systems, including some on the ground (determining the best flight attitude based on simulation of a variety of factors) and the plane and, possibly, the pilot. There is no longer a hierarchy of systems but a variety of systems interacting with one another.

Decision-making technologies rely on perception and awareness, recognition, learning, planning, knowledge representation and reasoning. The decision-making process combines pre-loaded data (*a priori* knowledge), sensor data processed to create awareness, and interactions with other autonomous systems, including humans, and infers goals and plans of other autonomous systems in its environment to create a set of executable actions. Actions are taken on the basis of an overall goal that needs to be achieved by the autonomous systems. The validity of that goal is not within the autonomous system to dispute, however, the means through which that goal can be pursued is within the autonomous system's decision bringing to the forefront ethical issues that in turn have an impact on the decision-making process and on the technologies used.

Several products for decision-making already on the market

Several products offering an integrated set of technologies for decision-making exist on the market and more will become available in the coming years as the number of autonomous systems and application areas will keep growing.

DARPA is funding several research projects aiming at decision-making in autonomous systems in a variety of situations and context:

- ONR LOCUST (Low Cost Unmanned Aerial Vehicle (UAV) Swarming Technologies) aiming at enabling decision-making in drones, normally controlled by an operator but able to act on their own by collaborating with one another if connection to the operator is lost
- ONR CARACaS (Control Architecture for Robotic Agent Command and Sensing) aiming at providing decision capability to autonomous boats for patrolling harbors and escorting ships
- DARPA ALIAS (Aircrew Labor in Cockpit Automation System) aiming at reducing the work load of pilot in military and commercial aircraft providing autonomous decision-making capability

## 3.3.2 Complex Systems Technologies

Symbiotic Autonomous Systems are complex systems since they are the result of several interplaying factors and change their behavior to adapt to changes in their environment. A single bacterium is a complex system; current artificial autonomous systems are much less complex than bacteria but still many fall under the category of complex systems.

Small World Theory

The sets of relations an autonomous system has with its environment can often be described through the theory of Small World with sets of weak and strong relations (links). This is because the number of relations, particularly for systems that move around, like a self-driving car or a drone, is quite large and the quality of relations varies a lot. Some of these relations are passive, like a car becoming aware of a dog while a few may involve direct communications (like car-to-car communications). Modeling of these relations is an important part of a successful autonomy.

The degree of complexity in an autonomous system includes both the system itself as well as the relations the system has to face. There are ways of measuring this complexity, like statistical complexity and self-dissimilarity. More work is needed in this area with specific reference of complexity in symbiotic autonomous systems.

Also, notice that telecommunications systems in general and the Internet specifically may be seen as complex systems for their high number of component elements and the variety of their interactions. With the shift from hierarchical architectures of the past, where complexity was managed in terms of hierarchy, hence highly reduced (one may claim that telecommunications electromechanical systems and even the first generation of electronic switches were "complicated", not "complex") to the flatter hierarchy of today, the complexity of telecommunications systems has grown and the advent of IoT with millions of them having an autonomous behavior that affect the overall network is further increasing this complexity.

Internet is a Complex System

The drive of telecommunications operators to manage in a rigid way the 5G network, also understandable in terms of limiting its complexity, may fail given the rise of the edges and their evolution in a chaotic way. It is most likely that 5G networks will have an increased level of complexity greater than current LTE networks. Applying complexity metrics to today telecommunications networks and simulating first, then measure, the complexity of future 5G networks may be a good topic of research with several practical effects. 5G, for its characteristics of being a communications fabric self-created at the edges by autonomous systems may prove to be a key component in their evolution. The variety of protocols that will be embedded in 5G provides the latitude required for communications between and within symbiotic autonomous systems.

5G as a Complex System

Several domains, like smart cities, health care, and production processes are becoming complex systems. Notice that while a *complex* system is, in a way, *complicated*, the difference is that complication is an essential characteristic of a complex system, and it cannot be reduced because the system is … complex. On the other hand, many systems are complicated but it is possible to reduce them into individual components each of which is "easy" and also the relations among them can be seen in subset making them "easy" (both to understand and manage). A complex system complexity cannot be reduced since complexity is an integral part of it. A bacterium can be "decomposed" in terms of its cellular organs, and the metabolic relations can be identified and separated. However, what you get from this decomposition is no longer understandable as a bacterium. It needs to be reassembled to observe and understand the overall clockwork. .

### 3.3.3 Emergent Properties Technologies

The relations among the various components (physical and behavioral) of a Symbiotic Autonomous System are perceived by the context as its *emergent properties*[19]. An emergent property is a property that the system has as a whole, but none of its component possess. Interaction with other systems and with the environment takes place through these emergent properties, since they are characterizing the SAS. Hence the decision-making happens at the whole system level and there is no specific component in the system in charge for it.

This happens normally in (insects) swarms where decisions emerge out of the collective behavior of the swarm and there is no individual component in charge. A set of autonomous flying drones can in principle be programmed with a central "intelligence/command", creating a hierarchy, or it can be programmed with a set of rules that results in emergent decisions. This latter approach has more resiliency since there is no "commander" whose loss

Hierarchy vs Emergent Properties

[19] *Emergent properties* are those found in a complex system but not found in or predictable by the characteristics or behaviour of the system's individual components.

would hamper the swarm activities. The Internet is an example of a massive distributed control for packets routing leading to an extremely resilient system from the point of view of end-to-end connectivity. At the very beginning of the Internet, routing strategies like the "hot potato routing" where studied and implemented to ensure a high reliability of networks connectivity. This has evolved in other variant, like the "cold" and "mash" potato routing, specifically designed for autonomous systems.

5G as a swarm like Infrastructure

5G at the edges may also be engineered as a swarm like infrastructure where the connectivity (at the logical level—data transfer) is managed in a collective way with no single entity in charge for routing. Massively distributed IoT may be engineered to form a "swarm" and to have the swarm as a whole in charge for taking decisions.

Autonomous systems operating in a symbiotic relation (such as micro-bots embedded in a living being) will need to make decisions in absence of a coordinator, using a completely flat hierarchy, and the decision-making process will be an emergent property of the symbioses. Studies of nature where these emergent properties are usual, like in bee swarms, starling flocks, and even brain decision-making processes, are leading to an understanding of basic rules that can be coded into single autonomous systems, and their components to give rise to "intelligent" decision-making processes.

# 4 Scenarios in Vertical Fields of Application

In this section of the White Paper, a few scenarios of operation of SAS are presented to provide an understanding of the latitude and impact that can derive from them and to stimulate a discussion among a wide constituency.

Each scenario is presented as a story with fictional characters. Each one can be read and discussed independently of the others. They are not claiming to be real; their feasibility will depend on many factors, technological as well as economic, social and regulatory. They are conceptually possible, although their actual implementation may require technologies that will not be available, or affordable, for quite a number of years or be undesirable from a social standpoint. This is a first set of scenarios. The aim is to modify them and add new ones as more insight and comments are gathered.

Before embarking on the following scenarios, we would like to know how important do we think this emerging field is to society. One way to measure the importance is to observe the trends of the next generation and what they are hungering for. If we look at both MIT and Stanford and the number of students enrolling in AI courses, the result leads us to the understanding that we are observing the largest growth ever in the areas of engineering and computer science. In 2017, the AI enrollment of just these two universities is approximately 2000 students.

The following vertical fields are considered:

*Augmented Humans*
The existence of SAS is bound to increase a person's physical and mental performance. This may lead to a gap between those who have access to SAS and those who do not.

*Smart Cities*
Cities are a cluster of systems. Several of these systems will acquire SAS capabilities and the city may acquire a life of its own. While on the one hand the emergent "city" would be more effective, the issues of control versus autonomy will have to be addressed.

*Earthquake relief*
In a catastrophe situation the availability of SAS may greatly increase the effectiveness of relief endeavor. The extent of independence and self-coordination among various systems is a crucial aspect to be addressed; aspects of accountability of an emergent entity versus the accountability of individual systems need to be explored.

*Industry 4.0 and 5.0*
Collaborative robots are starting to appear on production lines. Seamlessly collaborative robots will increase their range of application, will interact more effectively, and autonomously, with one another and with people. Collaboration will take place along the whole value chain extending to the retail point. Then it will move up into the usage domain. SAS will become production entities, co-designing with humans and self-adapting through the use phase. Eventually, some SAS will become the product and co-design of SAS will mark the shift to Industry 5.0.

## 4.1 Augmented Humans

Yesterday it was overwhelming with so many things to take care of: first the issue with a client upset for the delay in receiving the pallet, then it was the kid who fell at the gym and sprained his ankle, and to top it all a leak in the home draining system.

OK, in the end everything was "patched up" but still the stress of the day carried out through the night and Joseph didn't get the usual restful sleep and now as he woke up he felt a bit dizzy.

The problem with the pallet was a truck whose engine broke down, unexpectedly in spite of the monitoring system that should have warned of the risk and pressed for preventive maintenance. The company taking care of the logistics had to send another truck, unload the pallets from the one that broke down and load them all on the other truck but that took some time, and because of the priority of some of the packages they were taken back to the dispatch and rerouted on delivery vans to ensure keeping the schedule. That particular pallet was not tagged as "high priority" so it was simply rescheduled for delivery today, which the client didn't like a bit, hence his angry call.

It was sort of curious that with the automated logistics, self-driving trucks and continuous tracking of goods this mishap still happened. At least it was easy for Joseph to know immediately what the problem was as the infuriated customer called him, thanks to an add on memory that contained the updated situation of everything that was going on in the company and an application that matched the voice of the customer with his identity and the order placed. He had all this information in front of his eyes within a few seconds of receiving the call thanks to augmented eyes (actually just a pair of contact lenses that displayed the relevant information from his phone – he still used an old model, and earbud with a few TB of information and a full slate of connectivity channels, not the new ones that some of his colleagues had implanted in the jaw).

Symbiotic Augmented Memory

Seamless Augmented Reality

The possibility to have the situation in front of his eyes, literally, at least gave the impression that everything was under control and didn't make a bad situation worse.

The sprained ankle was really nothing worrisome but it led to some rescheduling of his wife's activities that cascaded to a rescheduling of some of his activities as well. Being away from home was not a big deal since communications with the home ambient system was seamless, and it didn't normally require the provisioning of specific instructions. Today, he would just the update his kid's profile to include his reduced mobility allowing virtual touch. Having the possibility to touch, virtually, the kid's ankle through haptics was not "curative" of course but it calmed down the kid giving him the perception that his dad was nearby and had the situation under control. The recent possibility of "remote touching" seemed at first like a gadget with limited use (they were advertised as "enriching" an ecommerce experience letting you touch the fabric of a jacket before deciding to buy it) but it actually turned out that being able to touch and be touched, virtually, provided a perception of closeness that voice alone could not deliver. Yes, there have been issues with improper use of this remote touching, discussions on the virtual privacy breach, imagine that –virtual privacy-, because you were touching a model of the object in the cyberspace and this touching might not be felt, in some instantiations, by the object (which is an issue if the object was another person's body). As you can imagine the porn industry was the first to leverage this feature at mass-market level and a new industry of "touch" sprang out of this technology.

Virtual Touch

Virtual Privacy

Actually, the virtual touch feature opened up, along with its possibility, a can of worms. How can you trust the sensation you get from touching a virtual cashmere wool shawl? Will it correspond to the real one you will get from the one delivering by the UPS drone? Is the eventual difference to be blamed on the application you used, on the prosthetics[20] giving you the touch feeling or was it an intentional cheating from the seller who created a model that is "just so" slightly different from the original?

[20] A screen, such as the one of a smartphone or of a computer, or the one embedded in the surface of the kitchen table, can deliver haptic touch sensations.

Besides, touching is a subjective sensation. What you feel when you pat your kid is difficult to relate to what your kid feels through that patting. (Of course, that goes for all sensation.) If my perception of that green color the same as yours? Virtual sensations just introduce more uncertainties to the equation.

In this case it worked. Joseph's kid felt his father's closeness when he touched his ankle and it felt good to both of them. And in the end the sprain was milder than first thought, as Joseph discovered once he got home and started to look into the leakage of the draining system, assisted, so to say, by his kid that wanted to know everything about it. What was the draining system? How does it work? Why was there a leak? How would dad fix it?

Joseph could answer these questions for his son, but better yet, he could "show" him the answers in detail. The leak has already stopped because the house management system closed the water intake. So there was no pressure to fix it, but he wanted to make it sure that water flow could be restored to prepare dinner.

Using augmented reality and the modeling of the house, it was quite straightforward to see the plumbing system through the walls, and he shared this with his son, pointing out the various ducts. Finding the origin of the leak was a bit trickier since the model did not provide any indication but by looking at the position of the pipes and how they joined with one another it was possible to make some reasonable assumption on where the problem might be.

If it were not for the annoyance of the leak, Joseph would have been mesmerized and appreciative, of the ease of home maintenance these days, with the possibility of seeing inside the walls like he had superpowers, while it was just a combination of digitalization of his house made by the constructor (actually the house was first created digitally, the design was explored through virtual reality, and was partly constructed from the digital blueprint using 3D printing facilities, partly on site and partly at some manufacturing factory).

To definitively determine the origin of the leak, Joseph dropped a tiny pill-like maintenance kit including a camera in the basin and let it sink with the water through the draining pipes. A magnetic wand, not too much different from the one doctors were using to check the status of his artery at his last check up, let him direct the camera through the pipes exploring the internal surface till he found the leak point. A tiny fissure, maybe caused by some structural stress as the house moved a bit as result of heat and cold. Luckily it was possible to fix it from the inside using the maintenance kit and operating it with his hands. Actually, he was using augmented hands with a glove-like prosthetic, that was emitting radio signals to map the movements of its hand and finger with the actions to be executed by the maintenance kit. In spite of technology and augmentation making Joseph life a bit easier, the stress remains in his and many other people lives. Possibly because stress is part of life and living implies, at least sometimes, to feel stressed.

Augmented hand

Joseph was reflecting on these things as he went to bed, and possibly that was why he found it difficult to sleep and get a rest. One of the things on his mind was the realization of the continuity existing between his body and the ambient, both the near and the remote one. He thought of the seamless way he could touch his son from afar, and the interaction with various autonomous systems, both the ones being part of his work and the ones being part of his home. It really gave the impression, now that he thought about it, that he was living in symbioses with many objects and systems and the fact that it only occurred to him to think about this now was a further proof on the integration, of the seamless symbiotic relationship, that has become his way of life.

Symbiotic

Augemented Cognition

Further down the road, Joseph's grandchildren may take for granted the benefit of real-time augmented cognition, comprising intelligence, logic, creativity, planning, knowledge, and memory. One of the approaches investigating this challenging and compelling scenario is the synthesis of a range of fields that are viewed today as unrelated.

Imagine your future self with a difference: unlimited photographic memory, faster and more lucid thinking, creating ideas and solutions with greater speed and ease, and other "upgrades"—all of which would require no devices, prostheses or implants, and would be experienced in real-time as an integral, fundamental part of our natural physiology.

Synthetic genomics

In this brave new scenario, synthetic genomics melds with biomorphic technological components to modify the genome to express neural tissue enhanced with predetermined advanced technological factors. These properties would dramatically increase our intellectual capabilities, thereby addressing a current concern expressed by luminaries and laymen alike – the accelerating capabilities, autonomy and ubiquity of sophisticated Artificial Intelligence being sought by researchers and developers—by offering humans the capacity to bridge the projected intelligence gap causing much of the aforementioned apprehension.

Synthetic genomics

For the adventurous, the step beyond augmented cognition on an individual basis lies what might best be described as the ultimate Internet of Things: real-time communications between the individual and intelligent cloud data and computational resources, external bio memory, and remote sensors and actuators, as well as having access (when desired) to real-time communications with augmented cognition-enhanced individuals. The primary challenge in achieving these possibilities is the development of a robust, high-qubit, keyless, sudden entanglement death-proof, real-time mobile quantum communications network.

While having multiple simultaneous conversations sounds unmanageable, in this case the key to making possible what is impossible today is augmented cognition itself. Yes, this may seem to be more science fiction than potential science fact— but while these cognitive augmentation technologies cannot be created today, a wide range of theoretical and experimental investigations of the components involved is making significant headway, with a hippocampal neuroprosthesis that restores the ability to form long-term memories in those who with traumatic brain injury.

If still not convinced, recall the words of Arthur C. Clarke's *Third Law of Prediction*: "Any sufficiently advanced technology is indistinguishable from magic."

## 4.2 Smart Cities

The interplay of autonomous systems generates an emerging behaviour

Visiting a new city as a tourist is exciting; visiting it as an engineer might be even more exciting, particularly in these times when technology dominates, although it is mostly invisible to citizens and tourists alike. It takes an engineer's eye, and some help from cities' managers and operators to look through the "application layer" and see the machinery at work.

This idea of an application layer[21], hiding whatever is making the city tick, can only come to an engineer, used to separate the layer seen by users to the many layers required to make it all work seamlessly.

To her trained eye the sensors detecting the flow of cars, trucks, people and goods are clearly visible, even though a casual passer-by will miss the

[21] This is the ISO layering of systems, a standard architecture that has been used in telecommunications for over 30 years and that has supported the creation of ever more complex systems ensuring feature interactions and enabling evolution supported by multiple providers.

ones embedded in the tarmac and those security cameras that can double as visual detection points. Clearly he will also fail to realize that the antennas providing radio connectivity to smartphones, vehicles, and more generally "things" (IoT) are actually very sophisticated sensors detecting many parameters and letting applications extract further meaning, from traffic flows to the attraction of a particular shop window, from the way people aggregate in an urban environment to the way they use resources.

Sensors everywhere

Each city pulses in its own specific way, so specific—actually—that one can create a digital signature of the whole city and through this signature separate it from any other cities. At the same time this signature consists of ever changing details and by looking at these details one (an engineer…) can tell if something is wrong.

Within this signature, like a fractal construction, the engineer can detect other signatures, each representing a system like the public transportation system, the waste management system, the goods distribution system, the power and water distribution grids. All these "systems" would probably be placed at layer 2, 3 and 4. Layer 1 would consist of wires, pipes and tarmac, while layer 5 and 6 are for the coordination of various systems and delivery of hooks, gates, handles used to create and deliver services.

Autonomous vehicles redefine the city topology

However, looking closer, as an engineer is bound to do, she will realize that something is different from this nicely laid out model that fit so well the cities of the past.

Self-driving vehicles are changing the way city roads are used. No longer are there signs indicating one way streets, rather depending on the traffic flow, vehicles behave like they were on a one-way street at a certain moment or on a two-way street at a different moment. At some times they occupy all the lanes in one direction, and a moment later they squeeze into a few lanes in a direction to free the others for traffic coming in the opposite direction. There is no control in a classical sense. It is much more likely a flock of birds generating amazing and ever changing patterns with no one in charge. There is no defined protocol to agree on a sharing of the road, rather each vehicle makes autonomous choices "sensing" the presence (and behavior) of other vehicles in the vicinity and applies local rules (basically: "let's not crash!").

More difficult to perceive are the mutual relationships among different autonomous systems. The digital signature of the overall vehicles flow has an impact on the public transportation flow and on the goods delivery flow. Each of these two systems are influenced by the overall traffic flow and self-adapt to achieve their goals, like maximizing transport capacity to meet demand, decreasing fuel consumption, speeding up delivery and so on. Again, there need not be an orchestrator and explicit negotiation among the various systems and their component parts. Rather, each one is autonomous and takes local decisions being influenced by the perceived context. Clearly, a smart city "brain", a control center with a global view of resources available and pending requests on access to these resources may provide directives to the various systems under its control and sometimes override local autonomous decisions, but in general the city relies on autonomous decisions that—normally—ends up in a desired emerging behavior.

Influence through awareness generation

Large panels are drawing engineers' attention. They are showing snapshots of the city state, both the present one and the expected evolution. They look a little bit like the weather radar map, showing the traffic loads in the different city areas and the expected evolution[22]. This "expected" evolution requires varied technology (sensors and data processing based on past experience – AI/Deep Learning) as well as sociology and psychology. The aim is to generate awareness among the citizenship and through awareness

[22] Interesting work in the area of visualization of complex interacting systems like smart cities have been done by the Carlo Ratti team at MIT – Senseable Cities project. http://senseable.mit.edu

influence their behavior. Citizens are “autonomous systems” and collectively they form an “autonomous system” that smart cities are learning to manage (influence) in very effective ways. More than that, smart cities can measure the degree of influence and work on improving it, at the same time making do with what is achieved.

Symbiotic relation among citizens and smart city

Citizens live in a symbiotic relation with the various autonomous systems characterizing a smart city. Notice that symbiotic is a bidirectional relation, and this symbiosis is a recent phenomenon among smart cities and its citizens. In the past the city systems influenced the behavior of its citizen but the reverse was not true, at least in terms of having short-term effects. Citizens’ behavior used to influence the city behavior through a planning process that city’s administrators run to adapt city resources to changing demands. In present smart cities planning still exist but the mutual impact is felt immediately as systems respond to citizens’ behavior and vice versa.

Panels are useful to provide a shared awareness among citizens. Personalized awareness is also useful and made possible by customized information made visible to single individual. Often this leverages augmented reality technologies, showing “meaning on the person ambient”, and it may involve a digital self that lives in the cyberspace along with the other digital copies of resources, systems and processes making up a smart city.

Digital twins enable new approaches to management of autonomous systems

The existence of a digital twin of a city (digital representation of the city in terms of resources, their behavior and the rules steering it) is a crucial enabler in the overall coordination of the autonomous systems. While each of these autonomous systems operates independently of the other (it is autonomous, isn’t it?!) and it is influenced by the others in terms of the local context it perceives, the digital twin exists in a space where locality is no longer an issue (bits are fundamentally de-localized) and simulation can study the global emergent behavior and stimulate contextual changes (and even goal changes that in turns result in a different reaction to a given context by an autonomous system). Notice the different approach and the departure from the ISO 7-layer model in the case of a smart city based on autonomous systems. The coordination relies on changing goals, not on prescribing specific actions. Autonomous behavior is at the core of the behavior and this requires strategy for influencing the reactions rather than prescriptive approaches that are very difficult to apply in a context of autonomous entities.

Structural 3D Printing

Already established, commercial 3D Printing has established a growing role in creating houses, hotels, office buildings, and other structures. Coupled with the ability to included metals, electronics and other functional components, 3D-printed structures of sophisticated complexity and individually unique designs will be available at dramatically less cost and time than today’s equivalent building would require.

Structural 3D Printing

Beyond today’s 3D Printing technology is the recently-introduced SAS process known as 4D Printing of SAS smart materials that, once printed, can autonomously transform their shape in response to environmental conditions that provide energy input (for example, heat, light or water), as well as to user requirements. The value of 4D-printing to Smart Cities is its applicability of these environmentally responsive shape change materials to all sizes of structures. This feature creates a wide range of potential auto transforming SAS systems that would be simpler and cheaper to create, but also inherently providing such systems that respond as and when needed.

Future uses of 4D-printed SAS materials therefore include electromechanical component-free robotics; houses can inherently respond to sunlight to continually optimize the embedded solar cells to track the sun and thereby power output; clothing that changes its structure based on weather; and a wide range of other devices that would provide additional features, flexibility, protection— and other benefits waiting to be discovered.

4D IOT Network

Moreover, in an SMS Internet of Things world, 4D materials-based products could be linked in a secure hyper speed future self-powering wireless Artificial Intelligence network, such that both Smart City structures, and inhabitants could automatically and continuously predict and adapt to environmental changes.

## 4.3 Earthquake Relief

The quake was much, much stronger than the ones we have been used to. For as long as I remember trembles were a part of life in this part of the world, and that of course prompted the construction of buildings that can withstand strong quakes.

Yet when Mother Nature decides to punch hard you can preserve the integrity of structures but the "infrastructure" is going to be hit heavily. When the Earth's crust is rising, pipes fracture, cables snap, fixtures pop out and shingles fall from the roof. Besides, not all buildings have been built in recent years; many go back tens and even hundreds of years, and their reconditioning to stand quakes can only go that far. There is also the additional problem of furniture inside buildings; they are supposed to be fixed to walls but you cannot fix tables and chairs and the items you place in chests and closets. They are bound to wave, roll and fall causing damage and hurting people.

Technology vs Economic affordability

Technology surely helps, and technology is not a problem. The problem is cost, and more than that the cost of its deployment. It is, as in most cases, a trade-off you have to accept—but then you can prepare yourself for the worst.

In the past, the first information that a quake struck came from outside of the area hit by the quake, and the worse the quake, the more difficult it was to understand what really happened. It could take days to get a clear idea of the impact of the quake and even weeks to map the damages. There may be destruction in an area and within that very area a few scattered unscathed buildings—and sometimes an old building, with no quake resistance, would stand beside one that was supposedly more solid. Likewise, within a building that stood apparently unscathed there may be injured people while in others apparently crumbled several people could be safe although difficult to reach.

Impact maps

Now it is different. In a few seconds the quake monitoring center is flooded by data that can be analyzed and turned into a quite precise situational map, showing the impact and pointing to where relief is most needed and urgent.

Smartphones as autonomous systems

Smartphones are playing a crucial role, acting as an autonomous system that interacts with several other autonomous systems in a symbiotic manner. Each smartphone has a sensor detecting acceleration that is effectively a quake detector. Clearly, it is way less accurate than the ones used in labs, able to detect a quake occurring thousand miles away, but smartphones, collectively as a system, compensate their low accuracy by being "exactly" where the quake impact is felt and by their huge number. The data provided creates a map made by thousands of sensing points, hundreds of thousands in a city, and software can work on these data to assess the impact in each location with fine granularity. Besides, the smartphones are related to people, and are connected to ambient and objects (IoT) hence they provide a context.

For a few years now controlling home appliances through a smartphone has been available. This involves local communications, and through signal processing it is easy to build a map localizing with fairly good precision each appliance and the relative position of the smartphone. This positioning does not require the GPS signal which is difficult to get indoor. Different time stamps can indicate if the phone (i.e. a person holding it) is moving or not, and the types of movement can tell of a critical situation.

Privacy vs Safety

Of course, getting these data requires the owner of the phone to release them (provide a permission), and some people are not releasing them for privacy concerns. There have been talks on regulating and forcing the release of data (ensuring their protection) exactly to cover emergency situations like this, but no action has been taken so far. The privacy versus safety debate is still on. Of course, the outcome of events like this push towards the release of data, mostly by creating awareness in the population rather than through enforcement.

5G enables the shift of smartphones towards autonomous systems

We had smartphones for quite a while but they were not "autonomous"; they depended on the availability of the network. They were "terminals", smart but unable to live without a network. Starting with 5G a new paradigm will take place: smartphones, as well as vehicles and a number of IoTs—a vehicle, by the way, is an IoT,—can create a network (a mesh network) by talking to each other and can serve as communication nodes. In case of a network failure, the smart phones autonomously connect with one another and eventually to the network using one smartphone that is within reach of a functioning network that plays the role of access point to the all meshed network. Smartphones haven't been designed to operate in a disaster area, but they do, because they have been designed to be autonomous systems. Software applications have been designed to make sense of data, and these applications are the ones that can turn the data generated by the embedded accelerator into information on the quake.

Besides, each smartphone can bring information on its local context, on the IoT that are connected with it, and on their relative position so that by looking at before, during and after it is possible to create a dynamic map of what happened.

The associated localization of this information allows the monitoring center to evaluate the impact (the acceleration strength and type matched with the location/type of construction can tell a lot about the effect). This information is also created within the area, so even if no connection to the center is possible people affected by the earthquake are aware of the situation and can provide relief in a much more informed way.

Symbiotic autonomous systems at work

Of course, SAS is more than smartphones! Several other systems are autonomous, able to take local decision and behave accordingly. The gas distribution system auto-detects leaks and halts the flow of gas; similarly, the water distribution system can proactively detect contamination and inject disinfectants in the water to keep it safe. Autonomous vehicles self-organize, exchanging information on passable routes and will direct emergency vehicles to the blocked areas. Of course, there are still plenty of "non-autonomous vehicles" but the drivers receive real time data on the status of the roads and can take informed decisions.

Overall the systems keep working within the rules of maximizing the use of resources based on demand; and clearly demand may shift significantly after a quake. Because they operate within a set of rules and goals it is much easier for a control center to adjust the goals and let the various systems to optimize their actions.

In spite of the improved design of buildings and infrastructures the magnitude of the earthquake resulted in high damage, with several buildings that folded onto themselves trapping people inside. Even in those that sustained the shock, people were hurt by falling furniture and objects and are waiting for help.

The first to provide it are the neighbors that, differently from the past, have updated information on the surrounding. The fact that cell phones still work, thanks to their capability of creating a self-standing local mesh network clearly benefits the situation. Notice that this network is being used to provide information on what is going on, not just for calling. So each phone can display a map of the surrounding areas with indication of critical situations with people in potential need of help (automatically detected by using AI to analyses the movement data provided by the cell phone along with its position in relation to other objects—GPS would be unlikely to work under rubble). Augmented reality is also providing help since it can transform data into easily understandable localized information.

Help in on the way, and it will get there rapidly, first by drones that will monitor the area autonomously coordinating the rescue grid and delivering first aid kits where they are needed.

Cyber-roaches part of the rescue team

As expert help teams arrive on site symbiotic bugs get deployed. These are augmented cockroaches, first developed in Japan and continued to be developed in several research labs[23]. They are symbiotic autonomous systems that can roam a crumbled building with a micro video camera that sends images back to the rescue team. The "cyborg-roaches" use their natural intelligence to move around, finding ways to penetrate the building while the cyborg part is used by the rescue team to direct the roach and to receive visual feedback. The electronic stimuli are to keep going forward; the roach brain will convert those stimuli in finding possible ways to go forward which may imply backtracking and looking for alternative fissures to overcome an obstacle.

Robotic swarms are also used although these are not as effective as a cyborg roach in going into a specific direction. They are more suitable for semi random searches. They have the goal to explore a certain area and coordinate with one another to cover the search grid.
More advanced swarms can interact with the ambient, "feeling" the electromagnetic fields generated by appliances and using them as beacons. They are actually IoT devices forming a network with other IoT. As more and more IoT technology is, present in an ambient the interaction—and awareness—becomes more and more effective.

Robotic swarms interacting with ambient IoT

IoT have a mirror state in the web/cloud and this mirror state, or digital twin, is used by simulation programs that supplement the swarms in their exploration. As they move around they update the mirror image of each apartment, building, and neighbor, and this updated version is used to reshape the goals and the searching space of the swarm.

Technology to digitally tag objects has been around for some time, and a few persons have bought into it embedding a tag in their body. This turns out very effective in a situation like this because that tag is mirrored in the cloud providing an exact relative location of the person (in relation to other IoT nearby) thus allowing a fast pinpointing of the location. Clearly the privacy concerns are evident and most people have not been inclined to adopt these tags out of these concerns. However, in situations like this, a fast and accurate localization can make all the difference.

Relief teams as autonomous systems in a symbiotic relation with their ambient

These tags have been evolving particularly on the software side, providing the means to create real digital twins in the cloud. These digital twins share with their real twin the same ailments, experiences and can be experimented upon—virtually—through simulation. A lot of the symbiotic relation with the ambient takes place at this digital level before being activated at the physical level and only when it makes sense. As an example, it is becoming possible to (virtually) try a cure on the digital self in an accelerated time space, and based on the outcome execute the cure on the real person. Instances of the digital twin are active at the same time to explore different avenues allowing the selection of the optimal one. This is also being applied in rescue situations where several factors have to be taken into account (like accept the risk to quickly remove rubble to extract the person or given its health status delay the rescue to increase safety?).

[23] Cyborg-roach for emergency rescue situations: https://www.scientificamerican.com/article/remote-controlled-roaches/.

Of course, the expert relief teams are all tagged, one way or another, and each component of the team is monitored in terms of position and activity, providing continuous feedback on the context, needs and threats. The human teams act as autonomous systems, and each member of the team is, of course, an autonomous system. Additionally, they are in a symbiotic relation with the ambient and its objects via the cloud. In a way it is not different from the past (apart from the symbiosis with the ambient through the cloud) but on the other hand, the progress in the science of autonomous systems is providing much more sophisticated ways to influence the autonomous behavior, rather than forcing it through a well-defined chain of command that in situations like an earthquake relief operation tends to break down, usually at the most critical times and situation.

The teams make extensive use of augmented reality technology and devices that seamlessly support their actions, and their actions in turn become part of the virtual world being used to augment the overall perception of the situation to each member of the team and to all involved in the operation.

Increased flexibility is both good and bad

There are plenty of life and death decisions that need to be taken in a situation like an earthquake; actually there are many more today with the advanced technology and increased information available that we have at our fingertip. In turn this places increased demand, and the availability of autonomous systems both complicates and simplifies the setting. It makes everything more complex because it introduces variables that are trickier to control (autonomy, by definition, is opposite to "standard" control) but at the same time we have greater flexibility and this can simplify actions or at least increase the slate of possibilities.

## 4.4 Industry 4.0 and 5.0

Interacting with clients has always been a fun and challenging task, and this is why several years ago I decided to open a shop selling appliances. I went through some hard times as the avalanche of online shopping chewed into my business, harder than I ever imagined when I started. Indeed, when I opened my shop at the turn of the century online commerce was already taking up, but I thought that by having my shop in an attractive location with a smart and ever changing window plus a customized relationship with prospective clients I could weather the storm.

I had placed all the latest tech in my shop, from the shop window to the shelves, and this worked out well in attracting people to step in. And, once in, I could cajole them into looking at some wares and most of the time selling them a bit. That has been quite an effort. Keeping the shop attractive by using the latest "selling tech" is a never-ending effort, and a quite expensive one too. In addition, you need to balance what would be feasible with what is usable (in a seamless way) by the prospective clients keeping an eye on potential undesired effects (like balancing the knowledge about a customer with the perceived breach in privacy).

In spite of my effort, the tremendous shift towards online shopping has hit me hard. I was, actually, on the point of giving up. Then, also thanks to my years long pursuance of innovation in retail, I found myself riding the wave of Industry 4.0 from the end point of retail. That, I discovered, was actually a good place to be because it opened up many opportunities.

Nowadays I am no longer (just) a retail outlet; I am a key player in the production chain which has brought back leverage with the clients and put me in the value map again. Sometimes I look back at the evolution of the retail experience and then I imagine what evolution will take place next: well through this exercise I see that the future evolution is going to be much more "expansive" than the one we had in the past and the concerns coming from the US with malls closing down because of the pressure from online commerce are not concerning me. Of course,

it will take a different kind of "retailer", with different skills and "network-relations" and I am not sure I can fit the bill, but at least the future is in my hands.
A long time ago there were practically no shops in my sector, appliances. There were small workshops; clients would knock at the door explaining their needs, and the artisan would work out a solution.

It was the advent of the industrial revolution, with its volume production, that started the shop business. Clients came in looking for a product that would reasonably fit their needs. The online shopping in these last 20 years expanded creating a gigantic mall, and the convenience of online shopping shifted the focus and habits of consumers.

Online shopping, of course, was made possible by the Internet, connecting any person in any part of the world to giant virtual shops that in turn, and seamlessly, connected the request to a variety of providers and through an ever more sophisticated value chain delivered the product to the buyer. Automated systems are playing a significant role: robots in the production plant increased efficiency and decreased cost keeping a high quality level; in the distribution chain robots fetch the desired product from long lines of shelves and bring it to a sorter that handles hundreds of thousands of packages[24] in a single day, something that would be impossible in a retail store (not mentioning accommodating hundreds of thousands of buyers in a shop!).

Autonomous systems at work in on line shopping

I rode the way of the online shopping by "upgrading" my shop to become a "brick and click"; shoppers would come to visit me, and I would help them to choose the appliance best fitting their needs and order it online for 24-hour delivery. I made that customer "my customer" by updating its profile so that next time he would come to my shop he will be recognized as a recurring customer and I could help him even more.

In the last few years we have seen a further transformation of products, of the way they are produced and "assembled." Most of the functionalities are now software based which in turn has pushed towards more open interfaces and has increased their sophistication. Part of this sophistication is in their capability to become aware, at different levels, of their environment and use that to their advantage. Software and sensors have transformed appliances into autonomous systems that can interact seamlessly with their users and with one another. The idea of a product has morphed into the one of "service." And now, I am in the business of customizing, even assembling, products and delivering services. Customers are flocking to my store because of this. Yes, there are plenty of ways to do the customization online, basically creating your own product, but for many people it is not easy and it is surely time consuming checking the different options and evaluating them. Clearly for some this is a great fun, but for many others it is stressful. Besides, there is the issue of taking responsibility of the result. And that is where I create value.

Industry 4.0 at the starting block

There is a word for this: *Multichannel Man*. Buying a product may mean accessing several channels each one providing a piece, and their integration results in the product. The sophistication, and complexity, is growing. Each channel is a system, and often these independent systems are built in such a way to communicate one another to state and understand requirements. Then they create their part accordingly so that in the end all parts fit nicely together.

This has started with the soft part of products, first through the publication of API (Application programming Interfaces) and ODF (Open Data Framework) then through plug-ins that work as adaptors across different parts and functionalities. Now also the hardware is becoming more and more customizable. The use of 3D printing is a reality at the point of sale. It has become both

3D printers as autonomous systems

[24] At peak time Amazon shipped 306 boxes per second, over 3 million per day in 2016!

more sophisticated and easier to use thanks to its growth into the autonomous systems family.

When a shopper enters my shop he has the possibility to look at existing products on the shelves and to “see” their variations through augmented reality. I usually provide them with a screen to view the AR although some are using their own screen, glasses, or smart phones to get the AR image.

He can combine the augmented vision with his own information/data to provide the specification of the product he would like to have. Here is where I step in. I can browse several producers’ “capabilities” (notice, not products but capabilities!) to see a fit and then I can orchestrate the various channels for delivery. Most of the time I can use one of the products I have in the store and add to it. For the software, addition it is quite straightforward (that is if you know how to do it and that is my competitive edge), and for the hardware addition I may turn to my 3D printers that will download the specs from a manufacturer and will adapt those specs to the specific needs. You might of course say that my 3D printers are just terminals but their sophistication and capability to make autonomous design choices to adapt the printing specs received by a provider to the needs of the customer makes them something different from a terminal.

They have surely become part of the production process, and they will enter in the service delivery chain. As the customer uses the product new needs may arise and some of them will be met by my 3D printer. For sure this applies to consumable parts that will require replacement. This replacement has become a smart process, since it takes into account the kind of use and wear and might result in a slightly different part being printed. As an example the wear on the product may require a slightly “bigger” part to be printed to compensate for the loss of material. However, this is not always feasible; sometimes you will have to replace also the other part or create an adaptor. All these decisions are taken by the printer itself since it has the understanding of the overall design and can take decision on the design of the component to be printed.

Production processes are becoming more and more autonomous

As a component in the manufacturing process my 3D printers are connected to various component manufacturers and provide feedback on the issues met in the integration thus enabling them to change their parts in a continuous quality improvement cycle. Production processing is increasingly evolving in the direction of autonomous systems, looking out for opportunity to deliver, and are ready to change their offer to meet the potential market. The designer remains a very important piece in this but the separation that used to exist between the designer and the production is more difficult to pinpoint. Now design and prototyping occurs at any stage and continuous feedback changes the production in a continuous evolution (this has been true for software for a few years now). Actually, I am also doing design and prototyping in the shop, based on requirements from my clients (and a few of them has started to design their own appliances from their couch and managed to get the final product according to their design by interacting with various producers in the value chain).

Platforms as enablers

The name of the game has become the consolidation of frameworks and platforms upon which a great variety of products and services can be created. The European Commission has invested quite a bit of money, as an example, on the FiWare platform. This has been used to make service creation, deployment and management in smart cities more efficient (reusability, faster deployment) but at the same time FiWare can be seen as an Industry 4.0 example. It can evolve in the direction of support to autonomous service creation.

The existence of such a platform is acknowledged even in my shop. Knowledge of its existence, functionalities and accessibility allows me to create appliances that take advantage of it. A refrigerator can interact with the Smart Grid to synchronize its compressor use of power with the grid. Yes, having one fridge doing that has no impact but there are hundreds of thousands of them and this can make a difference. And what about the electric cars plugged in the mains? Each one is tapping 26KW from the grid, a thousand of them means 26MW.

Self orchestration of autonomous systems

A customer asked me some time ago to have his fridge access the power in his car battery that in turn was storing power produced during daytime by its photovoltaic roof. Clearly the fridge, and the overall systems, needs to be smart enough to avoid drawing too much power from the car battery, and this in turn needs to take into account driving habits, weather conditions and much more. Actually, so much more that it would be too complex to design as a set of rules. What you need is the self-orchestration of different autonomous systems each one exposing its features and requirements and each one adapting to the changing context.

In the near future this complexity may be managed at the point of sale and at the point of use by the appliance itself. The assumption is that the appliance becomes a full autonomous system that is able to auto-adapt its behavior based on the context. This latter includes the space in which it operates, the other "occupants" of the space—like other appliances as well as people—and the goal that has been set. This latter is still my turf, and the reason why shoppers will still come to my shop. Sure, the end user will be able to define the goals, as well as change them as need arises, but the vast majority of users will still prefer to have a trusted third party (meaning somebody they can blame!) to take the task for them. The appliance, once provided with the goal and aware of its context, may—autonomously—proceed to enhance itself to better fit the activities required. The shopper has become, thanks to this autonomous appliance, an "*Omnichannel shopper*" in the sense that it buys through a single channel that in turns access the required channels. Interestingly the shopping is, in a way, done through the ambient of the shopper. In this case, it is done via the appliance itself.

Of course this is pretty convenient but at the same times it opens up a can of worms. How do you trust an object to do shopping on your behalf? This way of acquiring products (as well as services) hides quite a bit from your perception. On the other hand, this is typical with autonomous system; since they are autonomous you don't know what they are doing and you have to trust them. When a pilot flies with IFR (Instrument Flying Rules), she has to trust the plane (an autonomous systems); when you activate Roomba (the vacuum cleaner), you are trusting it to do the cleaning in a proper way. In the future, your Roomba may decide that given the new carpet you placed in the living room it would be better to buy a new software app to optimize the cleaning, and as it is trying it out it might, autonomously, provide feedback to the provider and change the periodic maintenance contract because of the expected different wear.

Autonomus systems become shoppers

Quite a bit of "shopping evolution." isn't it? We have been moving from

- going to the manufacturer (the artisan) to request a product by providing our "specs" to
- having manufacturers betting onto what we would be willing to buy and filling shops with merchandise, to
- accessing unlimited choices provided by e-commerce sites to the aggregation of parts (hard and soft), to
- creating our own customized product by assembling parts provided through different channels, to
- creating a shopping chain through the ambient, products/services we are already using.

Of course, this represents just a systematization of the evolution, with each subsequent phase becoming prevalent but with the previous ones still active, (we are still using artisans although this is the exception rather than the rule).

As a shop owner, I had to adapt and change through this evolution. In addition, more is on the horizon. I have been told that the evolution is towards a sort of integration, or symbioses, between the shopper/user and the product/service. This is called the "Integrated digital shopper." The novelty is that in some (and growing) instances when you buy something, that something is actually partly outside of you (as it has always been) and partly is ending up inside you, a software like medium that makes you a better fit with the product.

Products may include the "upgrade" of the human user

The selling proposition looks engaging: you want to buy a piano. What about buying a package that will provide you the skill to play that piano? Now, this looks like science fiction and it will remain so for a few more years but what about systems that through advance BCI can deliver Augmented Reality right when you need to interface with a product? Clearly hitting a piano key that you see highlighted with your fingers is nothing like "playing a piano," although it might help the learning process. (There have been applications highlighting the keys on a screen for several years now, what is new is that the highlighting takes place through AR and it is invisible to others watching you playing.)

What will happen in the coming years is a progressive augmentation of humans and this may go hand in hand with a growing symbiosis with products. Now, if this seems out of science fiction as I mentioned before one should recognize that the digitalization of humans has progressed significantly resulting in the creation of digital twins. The digital twin lives in the cyberspace and can be used by third parties (having been given access rights) to simulate products interactions (including drugs, actually this was the first application) and is being more and more used to create applications that customize the rendering of information (which in turns means the customization of experience). Hence, it has become more and more common to augment your digital twin to better exploit a product or a service.

This is becoming the telltale sign of the shift from Industry 4.0 to Industry 5.0, the embedding of the user in the product. Although ideas are still being discussed on what Industry 5.0 may be, there is a consensus that it will be characterized by a much stronger cooperation between humans and machines (robots/autonomous systems) throughout the whole production chain.

# 5 Ethical, Legal, and Societal Implications of SAS

The development of SAS-related technologies (both at the component and system levels) is progressing at a dizzying pace. Advancements in computing and processing power combined with sensor and software technologies in robotics and AI domains are fueling the exponential growth and the feasibility of such system-of-systems becoming commonplace in the near future. Several instantiations of what our intermingled life would look like are already becoming apparent as detailed in the previous sections of this White Paper. Human-machine (commonly referred to as Human-Robot-Interaction (HRI)/Human-Computer-Interface (HCI) in the literature) and machine-machine interactions, collaboration, and cooperation are no doubt exciting.

While it is irrefutable that these technologies are evolving at a rapid pace and that they have the potential to transform and positively impact the lives of humanity, perhaps equally concerning are the not-so-well understood and anticipated implications of SAS. Especially when the SAS involve a human being and if the symbiosis does not take into account the well-being of the human at all times (not deliberately but as a result of 'autonomous' symbiosis conflicts), this can lead to confusion and outcry when something goes awry and in some cases might lead to legal and liability issues. As such, it is imperative that ethical and society-centric implications are taken into account right from the design and development stages of SAS within the Symbiotic Systems Science (SSS) framework.

Regulation and governance considerations are of paramount importance if SAS is to become pervasive and benefit humankind to its fullest potential. Typically, regulations struggle to keep up with technology growth and lag way behind, which in turn tends to slow down innovation and preclude the societal acceptance.[25] In recent years, a few instances of this effect have been witnessed. For example, federal aviation agencies around the world have been formulating guidelines (including the Federal Aviation Administration, FAA in the US) on how the airspace should be regulated with respect to Unmanned Aerial Vehicles (UAVs). Although several exemptions and licenses have been granted to public and private entities, it is still a grey area with respect to safety, security, and privacy issues on what constitutes a violation, and how violators are to be prosecuted.

Regulation and Governance

Such concerns equally apply to Self-Driving Cars (SDCs). From an SAS view, the increasing levels of autonomy (corresponding to decreasing levels of human intervention) are very much within the purview of this Initiative. For the most part, the technology-aspects of SDCs have been worked out—though some issues remain to be proven and tested such as sensor operation during challenging weather conditions and range and resolution needed for urban conditions and highway speeds, however, the liability and legal issues have not been adequately addressed. In the case of SDCs getting involved in an accident, it is not clear where the responsibility resides: Does the liability reside with the car manufacturer or the software provider? In several states in the US, the liability still resides with the driver (who is not "driving" strictly speaking), and the legal and policy frameworks are still in the making. While "guides" and "best practices" have been proposed,[26] they are still not enforceable from a legal standpoint.

A related priority is the definition and instantiation of SAS standards covering a range of design and functional parameters such as structural and functional biocompatibility, a factor that will become increasingly important as SAS evolution produces technologies with ever-higher degrees of biology/technology integration.

Standards

[25] Klaus Schwab, The Fourth Industrial Revolution, January 2016.

[26] Federal Automated Vehicles Policy, Acceleration the Next Revolution in Roadway Safety, US Department of Transportation & NHTSA, September 2016, and Strategy for Automated and Connected Driving, German Federal Ministry of Transport and Digital Infrastructure (BMVI), June 2017.

For example, if SAS cognitive augmentation technology differs by design, manufacture or performance, those systems with less rigorous standards might experience inferior performance or failure, which in this case would be experienced as an immediate, potentially distressing experience of disorientation, communication isolation, and reduced cognitive function.

A potential consequence of *not* developing and implementing adequate security and standardization protocols is biohacking of implanted symbiotic autonomous neuroprosthetics, in which remote of neural information could potentially be both accessed and modified.

Biohacking

Long-term SAS evolution will provide a range of novel benefits. However, given our evolutionary proclivity for socioeconomic class hierarchies, a key SAS consideration will not be its availability, but rather it being available to *everyone*. In the emerging datacracy, those without the ability to purchase or otherwise acquire SAS enhancements will *de facto* define an underclass, which would contradict the value structures promised by SAS.

Universal availability

Other areas that require attention include the discussion surrounding robots and jobs.[27] With the development of co-robots that share the workspace with laborers in manufacturing industries, there have been confusions and contradictions that have served to increase the anxiety of the public. Again, as robots and humans work in tandem, the SAS Initiative is well positioned to contribute from both technical and ELS fronts.

These debates would no doubt require input from technologists, policymakers, and end-users alike, and the research and development, user, and regulatory communities have a responsibility and a significant role to play in order to arrive at clear-cut policies and procedures. As such, SAS is making a concerted effort to incorporate viewpoints from technologists and public policymakers on how to identify gaps, barriers, and to initiate a dialog between different stakeholders from industry, academia, and government.

The aim is to arrive at a mutually agreeable blueprint that quells concerns arising from privacy, security, safety, and ethical issues while not impeding innovation and technological progress. To understand the current and future implications of SAS technologies, emphasis will be placed on important factors that need to be taken into consideration such as environmental, cultural, political and socio-economic and resource constraints. These factors become especially important and need to account for unique considerations when SAS are designed for developing and under-developed economies in addition to developed ones.

In the area of human augmentation there are clearly strong ethical issues, such as:

- Will the potential of augmentation create a gap between the haves and the have-nots?
- Will augmentation be regulated or let to the individual decision (and economic possibility)?
- Will employers start to look for augmented individuals better fitting the jobs?
- Will augmentation turn into a sort of slavery, like being able to carry heavier loads or be immune to fatigue in working long hours turn into forcing people to do things they wouldn't have done before, protected by the impossibility of doing them?

The technologies that support datacracy, or algorithmic governance, could also usher in the emergence of a networked *direct democracy* as well as a *post-scarcity/post-capital* ecosystem. In a direct (or pure) democracy –as practiced in Switzerland– citizens vote directly (there are no elected representatives) on matters of governance such as laws, policies and bills, this being analogous to voting on a referendum in an indirect democracy. In addition, voting irregularities that have long plagued democratic voting may be addressable in an algorithmic direct democracy model utilizing ubiquitous, strongly encrypted, remote e-voting (online or digital voting) based

Direct democracy

[27] A Future that Works: Automation, Employment, and Productivity, McKinsey & Company, January 2017.

on blockchain technology.[28] This would simultaneously create anonymous, publicly accessible records of the voter ID[29], candidate ID and the time.

While post-scarcity and post-capital ecosystems are often seen as synonymic, this is not necessarily the case. In a post-scarcity ecosystem, resources are no longer scarce due to adoption of renewable clean energy; fusion power, which uses water for fuel, cannot lead to a meltdown, and powers itself by generating more energy than it takes to operate the fusion reactor itself); and ubiquitous molecular- and atomic-scale raw material used by future 3D printers to transform what are referred to as blueprints into a wide portfolio of objects, including foods, biological tissue and organs, mechanical and electronic products, tools and components, and other outputs – all at minimal cost. Moreover, natural resources are handled by a global algorithmic network (comprising advanced automation, Artificial Intelligence and robotics) that will perform all steps in the resource location-acquisition-processing-manufacturing-maintenance-distribution sequence.

Post-scarcity ecosystem

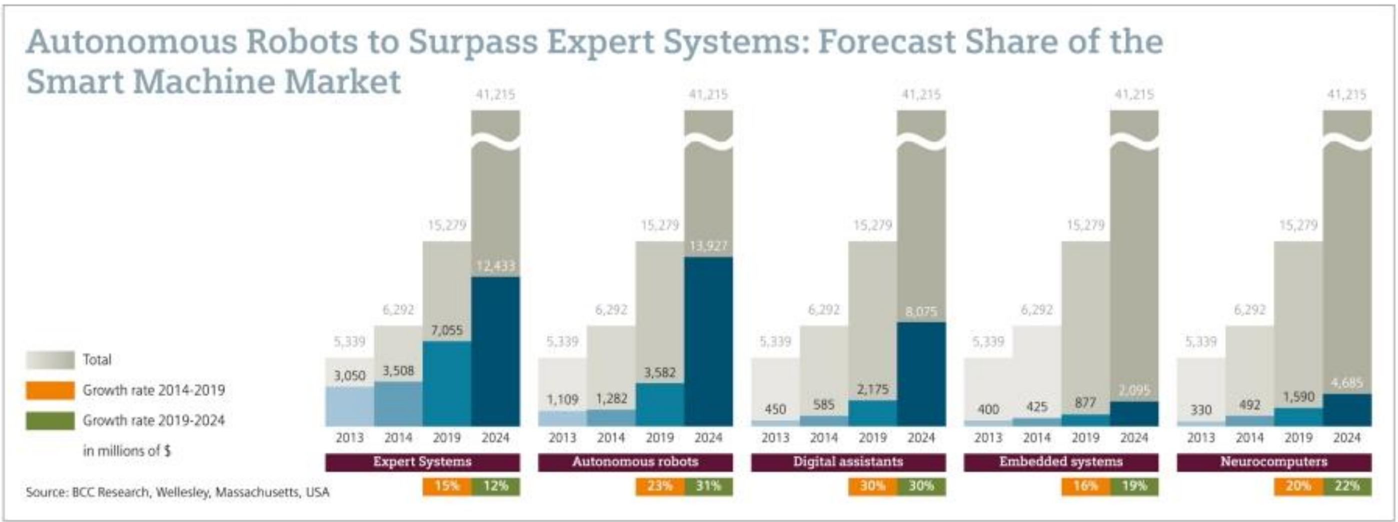
A fully automated SAS post-capital ecosystem (in which goods, services and information are universally accessible at no monetary costs) could then theoretically emerge when the above human labor-free system generates global economies of scale and algorithmic optimization to minimize costs to the point of making capital unnecessary, thereby transforming values and ethics that then prioritize societal well-being and global preservation. A post-capital supply-and-demand system could thereby leverage global crowdsourcing protocols and local/personal molecular manufacturing to operate automatically and perpetually optimize ecosystem operations, security and environmental issues addressed by datacracy-like intelligent algorithmic systems.

Post-capital ecosystem

[28] A blockchain is a database audit trail managed by networked computers. No single computer is responsible for database storage or maintenance. Any computer may enter or leave the network at any time without compromising database integrity or availability, and can rebuild the database by downloading the blockchain and processing the audit trail.
[29] In a blockchain, a voter ID is a public/private keypair that is untraceable to voter identity.

# 6 Market Impact

As this White Paper has made clear, the area of symbiotic autonomous systems is very broad, and generalization would be misleading when discussing market impact. Notice that it is expected to have autonomous systems overtaking, in terms of market value, Expert Systems by 2024 (see graph below).

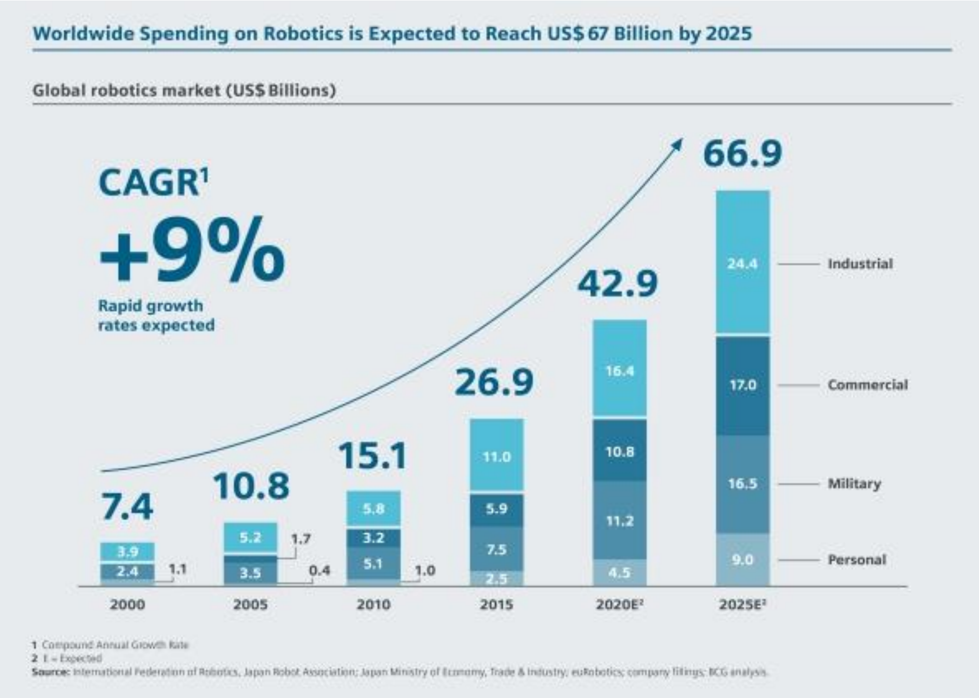



As a start, one can split the market into these area:

- robotic automation in manufacturing
- robots in transportation (self-driving vehicles)
- robots in health care
- robots in mass-market
- bio-prosthetic

## 6.1 Manufacturing

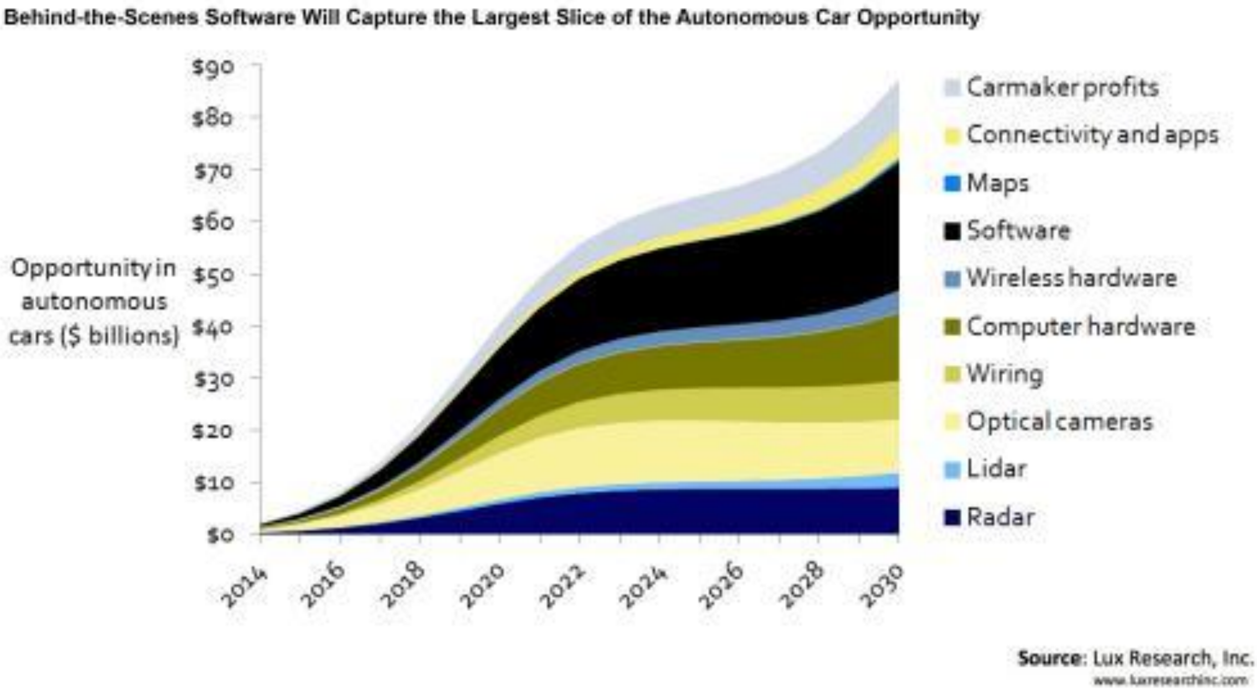
Penetration of robots and their drift towards increased autonomy will affect the manufacturing market significantly. On the one hand, it will threat the existing "way of doing things," and on the other it will grow the market of robots, their management and maintenance. As shown in the graph below the worldwide market in 2025 is expected to reach $66.9 billion (from a current market around $30 billion).




## 6.2 Transportation

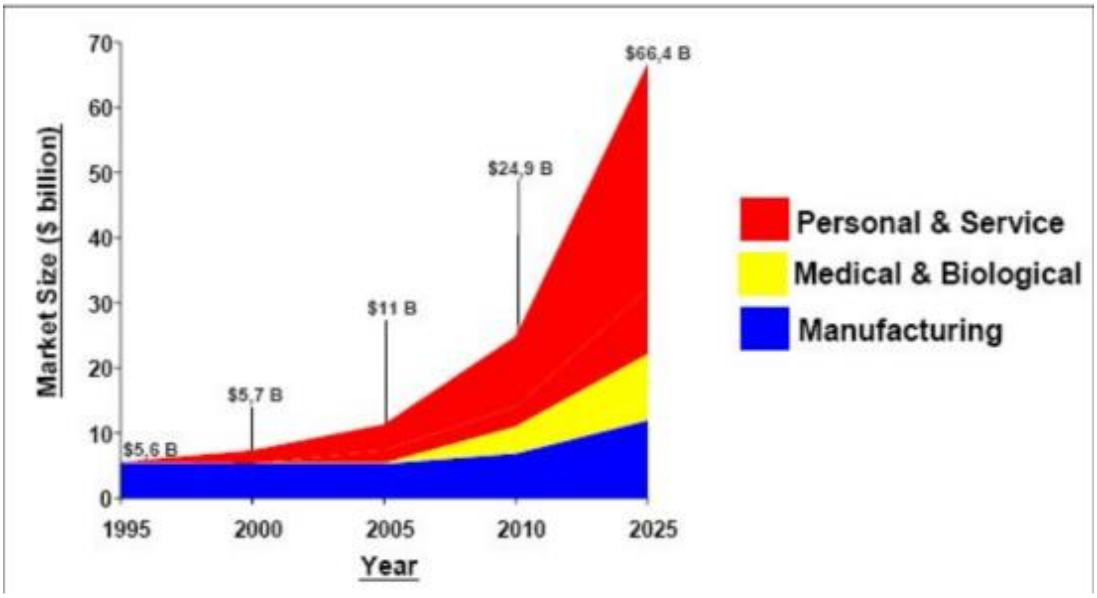
Self-driving vehicles are already a reality. The degree of self-driving is going to increase, from assisted driving to fully autonomous driving, and it will affect all kinds of transportation, from goods transport (platoons of trucks, delivery truck) to public transportation (buses, taxi) to private transportation. This will apply to road transport as well as sea shipping and air travel.

As shown in the graph, a major portion of the revenues will be absorbed by the software providing the "autonomy" with over $25 billion generated in 2030, versus a total of close to $90 billion for the whole sector.



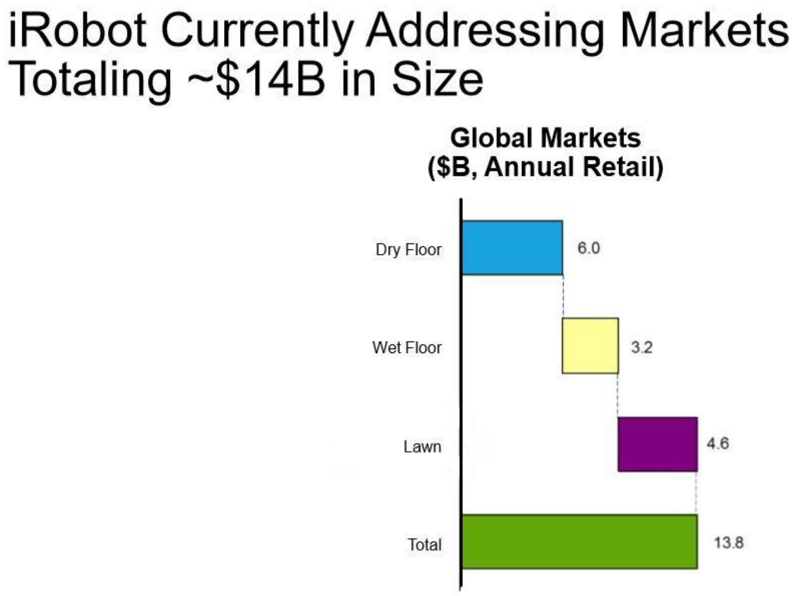
## 6.3 Health care

Robots are already widely used in surgery assistance and are starting to be used within hospitals to deliver drugs and assist patients. The big market growth, as shown in the graph (Source: Japan Robotic Association), is expected in personal assistance, particularly for elderly assistance at home. By 2025 out of an expected revenue generation of $66.4 billion, the personal assistance will generate some $40 billion.



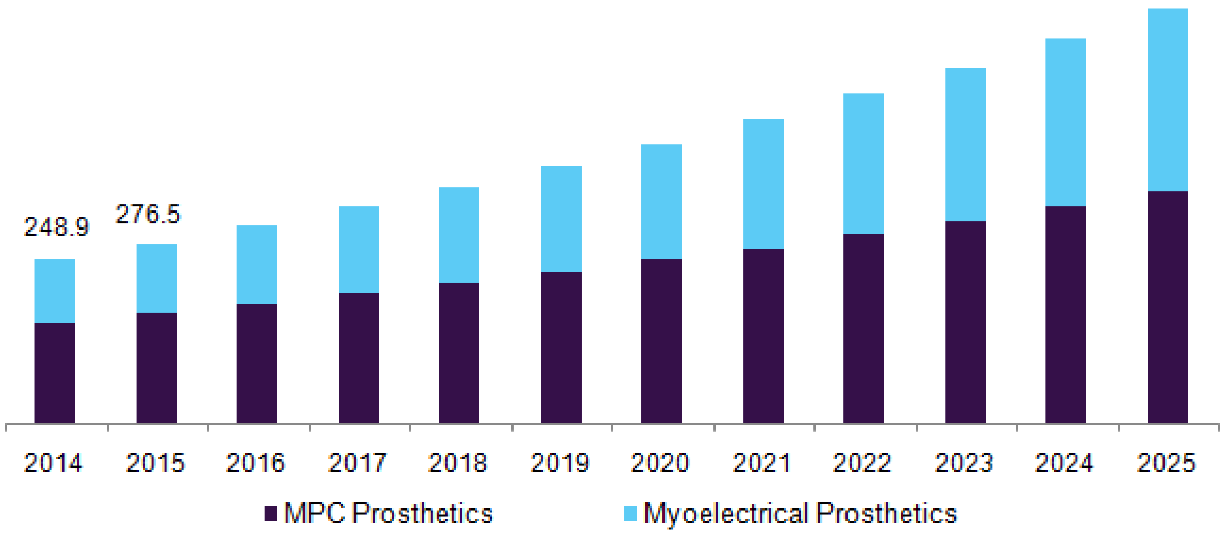

## 6.4 Mass-market

Autonomous robots are already a reality in the mass-market with possibly the most known example represented by vacuum cleaners. The addressable market is already significant, see graph (source: iRobot analyst presentation) totaling $14 billion worldwide.




## 6.5 Bio prosthetics

Robots in bio prosthetics are going to increase significantly as they will increase their capabilities, become seamless and decrease their cost. Just in the US, seen the graph, the revenue by 2025 is expected to reach $500 million, and several billion dollars worldwide. Of these, MPC (Microprocessors Controlled) will account for about 60%.




Bionics implants are expected to generate $17.8 billion in revenues worldwide with a CAGR of 7.1% in the following years (source MarketsAndMarkets)

## 6.6 Market Evolution

As discussed in the section regarding ethical and social implications, the theoretical emergence of a fully-automated SAS technology-enabled post-capital ecosystem[30] would have a profound impact on the concept of marketing and the practices of market analysis and strategy. The most obvious change would be that while supply-and-demand dynamics would still be operant (but achieved through universal crowdsourced networks), markets would no longer be measured in currency volume. Moreover, since shipped product volume is both the primary motivation and goal of market analysis and strategy in the service of a capital-based ecosystem, and assuming that a post-capital ecosystem—by being inherently post-scarcity in nature—would likely transform values and ethics by prioritizing societal well-being and global ecological preservation, market competition would then shift solely to reputation, design, features, and utility.

[30] In which goods, services and information would be universally accessible at no monetary costs.

# 7 IEEE Society Impact

The following table indicates the possible areas of impact of SAS on each of the IEEE Societies.

| https://www.ieee.org/societies_communities/societies/index.html | Interfacing Technologies | Control & Intelligence | Symbiotic Systems Science | Transportation | Healthcare |
|---|---|---|---|---|---|
| IEEE Aerospace and Electronic Systems Society | x | | | | |
| IEEE Antennas & Propagation Society | x | | | | |
| IEEE Broadcast Technology Society | | | | | |
| IEEE Circuits and Systems Society | | x | | | |
| IEEE Communications Society | x | | x | x | x |
| IEEE Electronics Packaging Society | | | | | |
| IEEE Computational Intelligence Society | x | x | x | | |
| IEEE Computer Society | x | x | x | | |
| IEEE Consumer Electronics Society | x | | x | x | x |
| IEEE Control Systems Society | | x | x | | |
| IEEE Dielectrics & Electrical Insulation Society | | | | | |
| IEEE Education Society | | | | | |
| IEEE Electromagnetic Compatibility Society | x | | | | |
| IEEE Electron Devices Society | x | | | | |
| IEEE Engineering in Medicine and Biology Society | x | x | x | | x |
| IEEE Geoscience and Remote Sensing Society | x | | x | | |
| IEEE Industrial Electronics Society | x | x | x | | |
| IEEE Industry Applications Society | | | | | |
| IEEE Information Theory Society | x | | | x | |
| IEEE Instrumentation and Measurement Society | x | | | | |
| IEEE Intelligent Transportation Systems Society | x | | | x | |
| IEEE Magnetics Society | | | | | |
| IEEE Microwave Theory and Techniques Society | | | | | |
| IEEE Nuclear and Plasma Sciences Society | | | | | |
| IEEE Oceanic Engineering Society | x | x | x | x | |
| IEEE Photonics Society | x | | | | |
| IEEE Power & Energy Society | | x | | | |
| IEEE Power Electronics Society | | | | | |
| IEEE Product Safety Engineering Society | | | | | |
| IEEE Professional Communication Society | | | | | |
| IEEE Reliability Society | | | x | | |
| IEEE Robotics and Automation Society | x | x | x | x | x |
| IEEE Signal Processing Society | x | x | x | | |
| IEEE Society on Social Implications of Technology | | | | | |
| IEEE Solid-State Circuits Society | | | | | |
| IEEE Systems, Man, and Cybernetics Society | x | x | x | | x |
| IEEE Ultrasonics, Ferroelectrics, and Frequency Control Society | | | | | |
| IEEE Vehicular Technology Society | x | x | x | x | |
| IEEE Technology and Engineering Management Society | | | | | |

| https://www.ieee.org/societies_communities/societies/index.html | Smart Cities | Smart Industry | Search & Rescue | ELS | HRI/HCI | Augmented Humans | Smart Automation |
|---|---|---|---|---|---|---|---|
| **IEEE Aerospace and Electronic Systems Society** | | | | | | | |
| **IEEE Antennas & Propagation Society** | | | | | | | |
| **IEEE Broadcast Technology Society** | | | | | | | |
| **IEEE Circuits and Systems Society** | | | | | | | x |
| **IEEE Communications Society** | x | x | x | x | x | | x |
| **IEEE Electronics Packaging Society** | | | | | | | x |
| **IEEE Computational Intelligence Society** | x | x | | | | | |
| **IEEE Computer Society** | x | x | | x | x | | x |
| **IEEE Consumer Electronics Society** | x | | | x | x | x | x |
| **IEEE Control Systems Society** | | | | | | | |
| **IEEE Dielectrics & Electrical Insulation Society** | | | | | | | |
| **IEEE Education Society** | | | | | | | |
| **IEEE Electromagnetic Compatibility Society** | | | | | | | |
| **IEEE Electron Devices Society** | | | | | | | |
| **IEEE Engineering in Medicine and Biology Society** | | | | x | x | x | x |
| **IEEE Geoscience and Remote Sensing Society** | | | x | x | | | |
| **IEEE Industrial Electronics Society** | | x | | | | | |
| **IEEE Industry Applications Society** | | x | | x | | | |
| **IEEE Information Theory Society** | | | | | | | |
| **IEEE Instrumentation and Measurement Society** | | | | | | | |
| **IEEE Intelligent Transportation Systems Society** | x | x | x | | | | |
| **IEEE Magnetics Society** | | | | | | | |
| **IEEE Microwave Theory and Techniques Society** | | | | | | | |
| **IEEE Nuclear and Plasma Sciences Society** | | | | | | | |
| **IEEE Oceanic Engineering Society** | | | x | | | | |
| **IEEE Photonics Society** | | | | | x | | |
| **IEEE Power & Energy Society** | x | | | | | | |
| **IEEE Power Electronics Society** | | | | | | | |
| **IEEE Product Safety Engineering Society** | | x | | x | x | x | |
| **IEEE Professional Communication Society** | | | | | | | |
| **IEEE Reliability Society** | | | | x | | | |
| **IEEE Robotics and Automation Society** | x | x | x | x | x | x | x |
| **IEEE Signal Processing Society** | | | | | | | |
| **IEEE Society on Social Implications of Technology** | | | | x | | | |
| **IEEE Solid-State Circuits Society** | | | | | | | |
| **IEEE Systems, Man, and Cybernetics Society** | | | | x | x | x | |
| **IEEE Ultrasonics, Ferroelectrics, and Frequency Control Society** | | | | | | | |
| **IEEE Vehicular Technology Society** | x | x | x | x | x | | |
| **IEEE Technology and Engineering Management Society** | | | | x | | | |

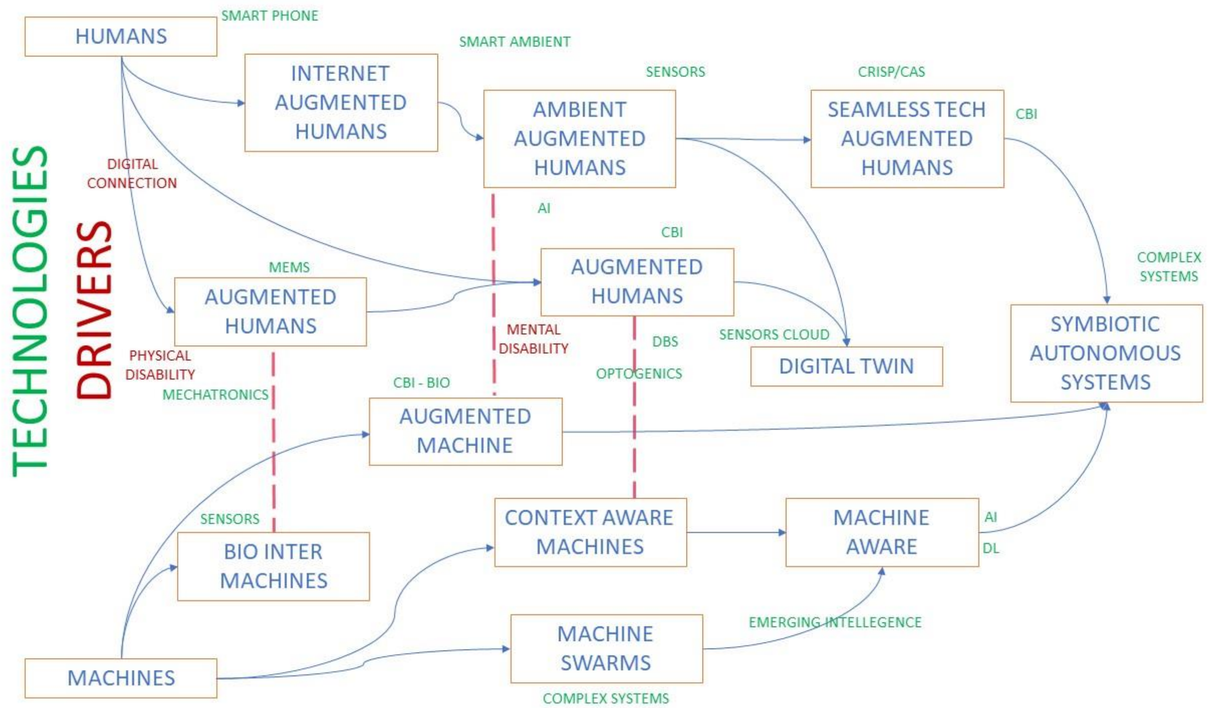
# 8 Further Notes on the Evolution of Machines and Humans

## 8.1 The Evolution of Machines

The Symbiotic Autonomous Systems Initiative White Paper is an interesting, thought-provoking document that in its concluding remarks outlines the expected evolution of machines towards awareness over the next three decades. (While the horizon has been set at 2050, current activity is significant, and much will be accomplished by the next decade).

Clearly it is difficult, perhaps unreasonable, to make predictions over such a timespan. However, the SAS White Paper is not based on pure speculation; rather, it is about evaluating today's technology, global research efforts, market demands, and social drivers that will make the evolution a reality. IEEE is aware of most technological research efforts—a global visibility that makes prediction in the area of Symbiotic Autonomous Systems an exercise in rationality.

To that end, let us take a look at the SAS framework:




Machines are becoming continually smarter thanks to ever-increasing processing capability, access to large storage for local and remote data, sensors, and communications. We have cars that have shown the ability to drive autonomously (although they are still rare, expensive, and face regulatory hurdles). In short, while the basic technology for self-driving cars exists today, it is neither completely practical nor affordable—but resolving these limitations is just a matter of time, not possibility.

These self-driving cars are *context aware*—that is, they "understand" (in an operational sense) what they need to do given the context around them. They can identify a person walking on the sidewalk and evaluate the probability of him suddenly crossing the road, as well as determine an incoming car's distance and velocity in order to evaluate the safety of overtaking a preceding car.

In the next decade, this context awareness will become more and more generalized and, most importantly, affordable—and not just for cars. Robot vacuum cleaners, for example, already have a rudimentary contextual understanding that will grow to include something like "there is a person watching a television show, so it is better not to disturb him and wait to clean," or "lunch is just finished so it may be a good time to vacuum the kitchen."

Note that a significant contribution to the evolution towards *context aware machines* might come from military applications, as has happened with other technologies in the past. In other words, it is not difficult to forecast that machines will become context aware wherever and whenever it makes sense.

We are already noticing that a number of devices are interfacing directly with us—primarily in the medical space—getting information on our status and acting in consequence. Insulin pumps are becoming smarter, providing the exact dose by measuring the glucose directly in the body (via smart contact lenses now in Google and Samsung labs, and most likely in other research labs, to detect the sugar level in the tears and communicate it to a chip that can autonomously deliver the required amount of insulin). In the next decade, these devices are likely to become proactive, analyzing and predicting behavior in order to deliver insulin before the user's blood sugar level becomes too low or high. *Biointerfaced machines* will allow them to connect to nerve termination, the metabolic system, muscles, our senses, and even directly to the brain. Hence, an evolution that we can expect is towards *augmented machines* that are enhanced through the information provided by a living being, including, of course, ourselves. Again we are seeing the first occurrences, although crude, of augmented machines in robots like Baxter, the Rethink Robotics industrial automation robot, that learn by watching people, or in sensors leveraging living cells to detect specific molecules. Of course, it can be said that tools are "augmented" by people using them, but in this case, we are not talking about autonomous systems. A hammer cannot do anything without a hand (and a brain behind the hand) operating it. A self-driving car, on the contrary, can operate autonomously but it can also benefit from a driver standing by. In the coming decade the situation where people can "lend" their brain to a machine to augment its intelligence will become more and more common.

In order to become "intelligent" a machine, like living things, needs to pass a certain threshold of complexity. A bacterium is operational and, in a way smart, but that intelligence is the consequence of millions of evolutionary steps over a myriad of generations that finely tuned its response to the environment. However, a *local* intelligence requires much higher complexity. While not all machines will reach this threshold, some will aggregate into complex systems from which intelligence will emerge. These *machine swarms* are becoming possible through a connectivity fabric that connects thousands to millions of them, much like anthill intelligence emerges from thousands of ants that are individually incapable of showing intelligence.

Both machine swarms and context-aware machines will likely take the further step of becoming *machine aware*. In a way, complex living things are an example of this evolution: One can see our human body as a cell swarm, comprising hundreds of billions of cells, connected to a context aware machine, the brain, that all together result in a being that is "aware." Would these machines be "sentient" in the sense of being aware that they are aware? Opinions differ and no stand has been taken by the SAS White Paper in this regard.

## 8.2 The Evolution of Humans

Cleary humans have evolved. Our lost ancestors were different from us in shape and most notably in mental capabilities. This evolution occurred over hundreds of thousands of generations, and it is only across these long periods of time that it becomes visible. Going back 2000 years, or even 10,000 years is unlikely to show any difference. A Neolithic human born today would be perfectly capable of running a start-up or working at a stock exchange.

Nevertheless, we are now seeing an inflection point; evolution is accelerating, and technology is the root cause. A person with a physical disability, like missing a foot, can now use a prosthetic that can help coping with his disability. Actually, these prosthetics are becoming more and more effective emulating the real thing and providing a full function restoration. In a few cases, we are seeing an increase in functionality, be it the capability to be a better rock climber or having a better sight.

Indeed, the goal of fighting physical disabilities and restoring functionality is driving the evolution of prosthetics in hearing, seeing, walking, and recently memory and cognition. Exoskeletons are offering the hope to paralyzed people of becoming independent again: evolution in Brain-Computer Interfaces makes the control of prosthetics seamless, and although it will take several more years to reach this point, it is again a matter of *when*, and no longer of *if*. Prosthetics are leading to *augmented humans* and we are already starting to see the first examples of prosthetic to overcome mental disabilities, like Obsessive Compulsive Disorder (OCD) that can be treated (in a growing percentage) through Deep Brain Stimulation (DBS).

Even though the goal of helping people with different kinds of disabilities is driving the evolution of prosthetics, the augmentation of humans through a seamless adoption of technology is not progressing as rapidly.

As a species, we are already becoming *Internet Augmented Humans*, with the smartphone acting as a prosthetic device. Our memory and even our problem-solving capacity have expanded enormously. Today we "know" the date of the death of Napoleon as well as the cubic root of 43,967: they are just a few clicks away, and we no longer think about using the smartphone—we (even young children) just use it, as in the past we would have used pencil and paper.

As smartphones become more and more effective, and eventually morph into something that is indistinguishable from ourselves, we will evolve into a species that extends into the Internet, as we are extending today into the (mostly invisible) delivery chains. We have become part of a complex environment without which we will not be able to survive. Our life expectancy has doubled in the last 100 years, thanks to clean water and medicine, and yet 99.99% of us haven't the slightest idea on how to make clean water or medicines. Education is slowly changing in regards to the existence of the Internet; it is getting more important to know *how* to fetch the right information through the web than to *memorize* it by endless repetition.

The next step awaiting us in the coming decade(s) is an increased reliance on a responsive ambient, extending our reach. We will then become *Ambient Augmented Humans*. We are already seeing the first signs with Amazon Echo, Siri and the like. The ambient "listens" to us and is getting more and more aware of whom we are, what we need, and even what we "will" need. The ambient is more and more populated by smart objects that can shape their behavior to fit ours.

The presence of sensors, embedded or wearable, is providing more and more data that are creating a *digital twin*—a virtual self in cyberspace. The first instances of this digital twin, initially mirroring only a few aspects (but becoming a faithful copy with more, including our genome and metabolome), are being created to improve healthcare monitoring, particularly for people experiencing some form of physical and mental disability. This will soon expand to include all of us, again first for healthcare monitoring (proactive healthcare), and then expanding into what some are predicting to be an immortal existence in digital space.

The creation of digital twins for most people will transition through a *Seamless Technology Augmented Humans* stage. Part of this technology will likely be embedded in the ambient, and part in our bodies.

## 8.3 The Convergence of Humans and Machines

Technology is not just evolving our machines. It is creating a bridge between our machines and us. Biointerfaces are enabling seamless communications between our body, our mind and machines. This is clearly being exploited by improved and novel prosthetics that fit naturally to replace a lost functionality, as well as future prosthetics that augment an existing functionality.

Coming context-aware machines will serve even better interaction with humans as well as the eventual shift towards machine awareness, thereby leveraging their intelligence and complementing and augmenting ours. This is bidirectional: our intelligence will also augment machine intelligence (in the first phases, already today, our intelligence augments machine effectiveness) creating a world where cooperation is among humans, among machines and among humans and machines. This cooperation may be a loose one, occurring occasionally as interaction arises between two entities as they happen to operate in the same space; or it can become continuous, taking the form of a symbiotic relation. The latter may result in the creation of a new species of superorganisms, as envisaged by the Transhumanism movement. The FDC SAS Initiative is not taking any stand on this, but simply takes notice of this philosophical movement. The Initiative is focusing on the technology that can make these symbioses possible (requiring a seamless interaction and self-adaptation by the various components engaged in the symbioses) and on creating a factual field where Ethical, Legal and Societal issues (ELS) can be discussed and addressed.

In a symbiotic relation, there is an implicit creation of a superorganism and an issue of accountability arises. To what extent superorganisms are actually recognized as an independent entity (hence potentially held accountable), and to what extent accountability remains in its components, is a difficult question, since the behavior may not be a sum of behaviors exhibited by each component (in which case one could direct the accountability to a specific part); rather it might be an emergent behavior where the contribution of each part is no longer meaningful.

A strong symbiotic relation also implies that its components can no longer operate independently of one another. As noticed previously, we, humans, are already living in a symbiotic relation with our ambient to the point that if we were transported to a completely different one—in the jungle—we would be unlikely to survive. Hence, the evolution towards symbiotic autonomous systems, where we would be a component, is in a historical context, not radically new. This implies that there may be reason to advocate for weak symbiotic relations only so that we can remain an independent part that is simply taking advantage of symbioses when this is feasible, and living independently when not. However, also this approach creates significant ELS issues. It is clear that a symbiotic relation confers advantages to its participants and at the same time creates a gap with those that, for any reason, cannot engage in that relation.

For example, the gap created by the Have vs. Have Nots dynamic risks being more significant than the one we have today between those who can access technology and those who cannot. The reason is that while today the use of technology is explicit, in a future symbiotic relation it may become invisible. The advantage given to those that can have, as an example, their brain connected to the Internet versus those that will be able to access the Internet via smartphone is much wider than the one we have today between those that have Internet access with their smartphone and those who have no Internet access. The former will have increased access to knowledge and increased intelligence; the latter will only have "delayed" increased knowledge.

Another aspect that needs to be faced is the lack of a clear boundary between a symbiotic relation and a mediated one. Because there are no boundaries around intelligence, it will be difficult to perceive a disruption point—although we are clearly seeing that we are close to an inflection point where convergence of various technologies is reinforcing their evolution and usage.

# 9 Conclusion

Autonomous systems are already a reality; they are here to stay, and they will grow in number and functionalities over the coming decades pervading through all walks of life impacting the economy, the society, and individual lives.

Continually evolving technologies make these systems capable of performing at higher levels of autonomy demonstrating behavior that approaches that of human species. This raises a host of ethical, legal, and societal concerns and requires a concerted effort from many parties - not only those with a factual understanding of technology evolution and its impact, such as IEEE, but also social scientists, economists, policy-makers, and ethicists.

By researching current technologies, identifying those emerging, and describing their ethical, socioeconomic, legal, and technology policy impacts, the Symbiotic Autonomous Systems White Paper first described a detailed interdisciplinary path from the past through the present and into possible futures through 2050. The White Paper identified primary technologies grouped into key areas: Advanced Interaction Capabilities (sensors, actuators, cooperative support, human augmentation); Self-Evolving Capabilities (awareness and sentiment analyses, machine learning, self-replication); Autonomous Decision-Making Capabilities (decision-making, complex systems, emergent properties, cooperative support, human augmentation); and Autonomous Decision-Making Capabilities (decision-making technologies, complex systems technologies, emergent properties technologies). The SAS White Paper presented a robust, multidimensional roadmap to the most likely possible technological futures, their sociocultural implications, and narrative scenarios illustrating the contexts and implications in education, healthcare, smart cities, industry 4.0, consumer electronics, and diverse applications fields. The White Paper finally concludes that while future Symbiotic Autonomous Systems carry profound utility and potential, associated challenges may require attention to educational, sociocultural and legal aspects.

The FDC SAS Initiative views this White Paper as a call to all IEEE Societies and Councils to join forces in this exciting and impactful area, since IEEE as a whole has the resources and capabilities needed to lead in many areas, including standards, education, cutting edge research and innovation. The Initiative plans to engage IEEE experts and develop areas of mutual interest in the framework noted previously.

SAS is bringing to the fore a new paradigm – Symbiotic Systems Science - in which machines and humans interact in more effective ways, sometimes below the level of human perception. This interaction, which is anticipated to occur in the following decades, will augment humans, opening up new possibilities and challenges. Promoting and further developing this science is one of the goals of the SAS Initiative.

Further to that, we expect that the SAS Initiative will provide the visionary and luminary perspective needed to develop and evolve these systems over the next 10, 30, to 50 years. Parallel with the research and development of technologies to enable these systems must be an effort to continuously study the social, ethical, legal, and economic impacts these systems will have on society, driving the need for an SAS Initiative to collaborate, develop, and communicate these varied issues.

IEEE Societies (see Table) can contribute significantly by considering the aforementioned evolutionary developments in their conferences, journals, magazines, and educational programs, as well continuing revisions to this White Paper. The FDC SAS Initiative will provide a platform to bring Societies and Councils together and will continue to be the symbiotic glue that facilitates their autonomous engagement.

Visit the IEEE SAS web portal to learn, contribute, or participate: https://symbiotic-autonomous-systems.ieee.org/

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# 11 Glossary

**Autonomy**
The ability of a system to be able to act independently and intelligently in dynamic, uncertain, and unanticipated situations. In addition, an autonomous system should be able to detect when its goals stand in conflict with the laws that govern its behavior and must have a way to "fail" gracefully in those situations.

Often varying levels (modes) of autonomy are used in the literature. There are four modes of operation: 1) in the *Fully autonomous* mode, the system operates without human intervention while adapting to operational and environmental conditions, 2) in the *Semi-autonomous* mode, the human operator and/or the system plan(s) and conduct(s) a mission which requires various levels of human-robot interaction. It should be noted that the system is capable of autonomous operation in between the human interactions (also called "bounded autonomy"), 3) in the *Teleoperation* mode, the human operator, using sensory feedback, either directly controls the actuators or assigns incremental goals on a continuous basis, from a remote location, and 4) in the *Remote Control* mode, the human operator controls the system on a continuous basis, from a remote location via only her/his direct observation.

**Emergence**
Complex systems, i.e. those systems composed by many parts that cannot be reduced without a loss of function (complex systems cannot be simplified without losing some of their characteristics, while complicated system can), often show characteristics that are not present in any of their components. This is often the case when one or more of their component is autonomous. The behavior of a system that is not the result of one of its component but that results from the interaction of the behavior of its constituent parts is called emergent behavior and the property of these systems in creating a whole "behavior" is called "emergence."

**Evolution**
A system *evolution* leads to a new system with different capabilities, forms and behavior. This resulting system (that can be software, hardware or a mix of both) inherits some of the previous systems characteristics but has new ones usually as response to changing needs or to be more fitting to a certain environment. In this sense the word "evolution" reflects the concept of evolution in living beings. The evolution itself can be designed from the external or it can be generated internally, as an example by software applications that change their behavior as a consequence of experience. As in living species, autonomous systems can be designed to face and respond to selection pressure in various ways. Some routing strategies in the Internet have been designed to evolve in response to the success rate in establishing effective communications. In the future many software applications will be designed to be capable of self-evolution and the interactions among autonomous systems is also likely to evolve over time.

**Implicit/Explicit Communication**
Autonomous systems are equipped with sensors that allow them to construct a model of the environment in which they operate and applications that can create awareness based on the dynamically changing condition in the environment. These applications are able, to different degrees of sophistication, interpret these changes. This results in what is called *implicit communications*. The behavior of an autonomous system, as well as any other system, creates data that once analyzed provides an implicit communication. As an example, a car blinking its direction lights provides an implicit communication to other cars in the vicinity that it is about to change direction. On the other hand, a system can generate a stream of data coding the information that it needs to share with other systems (autonomous or not) based on an agreed standard. This is called explicit communications. As an example a car can broadcast its position and velocity to all nearby cars to let them know of its approaching a blind crossing.

**Internal/External Communication**
Autonomous systems are composed of several parts that communicate with one another.

Depending on the needs, *internal* communications may take a variety of forms that are "pre-designed." An autonomous system may also need to communicate with other systems, autonomous or not, and that "*external*" communication is also "pre-designed." There is, however, the possibility that autonomous systems moving in dynamically changing context may require establishing communication with other systems that were not known at design time. This *external* communication is a challenge that engineers need to face, and solutions are part of ongoing research. Basic standards can be defined at the physical and transport layer while communications at the upper (applications) layers need to be flexible to meet unknown requirements.

**Isomorphic**
Similar to. An object A, physical or abstract, is said to have an isomorphic relation with another object B, when it is possible to establish one or more mutual relation between the two objects. The isomorphism is tied to a specific relation, like a dog and a cat are isomorphic in terms of number of legs and tail. Analogies, on the contrary, reflect abstract similarities but are not necessarily isomorphic. As an example: I don't understand a word, it's Greek to me >>> what I hear is analogous to hearing Greek, since I do not understand Greek, I do not understand what it is being said now.

# 12 Acronyms

AI: Artificial Intelligence

ALIAS: Aircrew Labor in Cockpit Automation System

API: Application Programming Interfaces

BCI: Brain-Computer Interface

BMI: Brain Machine Interface

CARACaS: Control Architecture for Robotic Agent Command and Sensing

CBI: Computer-Brain Interface

DBE: Dynamic Brain Emulation

DBS: Deep Brain Stimulation

ELS: Ethical, Legal, and Societal

ENG: Electroneurogram

EMG: Electromyographic

HCI: Human-Computer Interface or Human-Computer Interaction

HRI: Human-Robot Interaction

IoT: Internet of Things

MEMS: Micro-Electro Mechanical Systems

MPC: Microprocessor Controlled

ODF: Open Data Framework

SAS: Symbiotic Autonomous Systems

SDC: Self-Driving Car

SIM: Substrate Independent Mind

SSS: Symbiotic Autonomous Science

TMS: Transcranial Magnetic Stimulation

UAV: Unmanned Aerial Vehicle