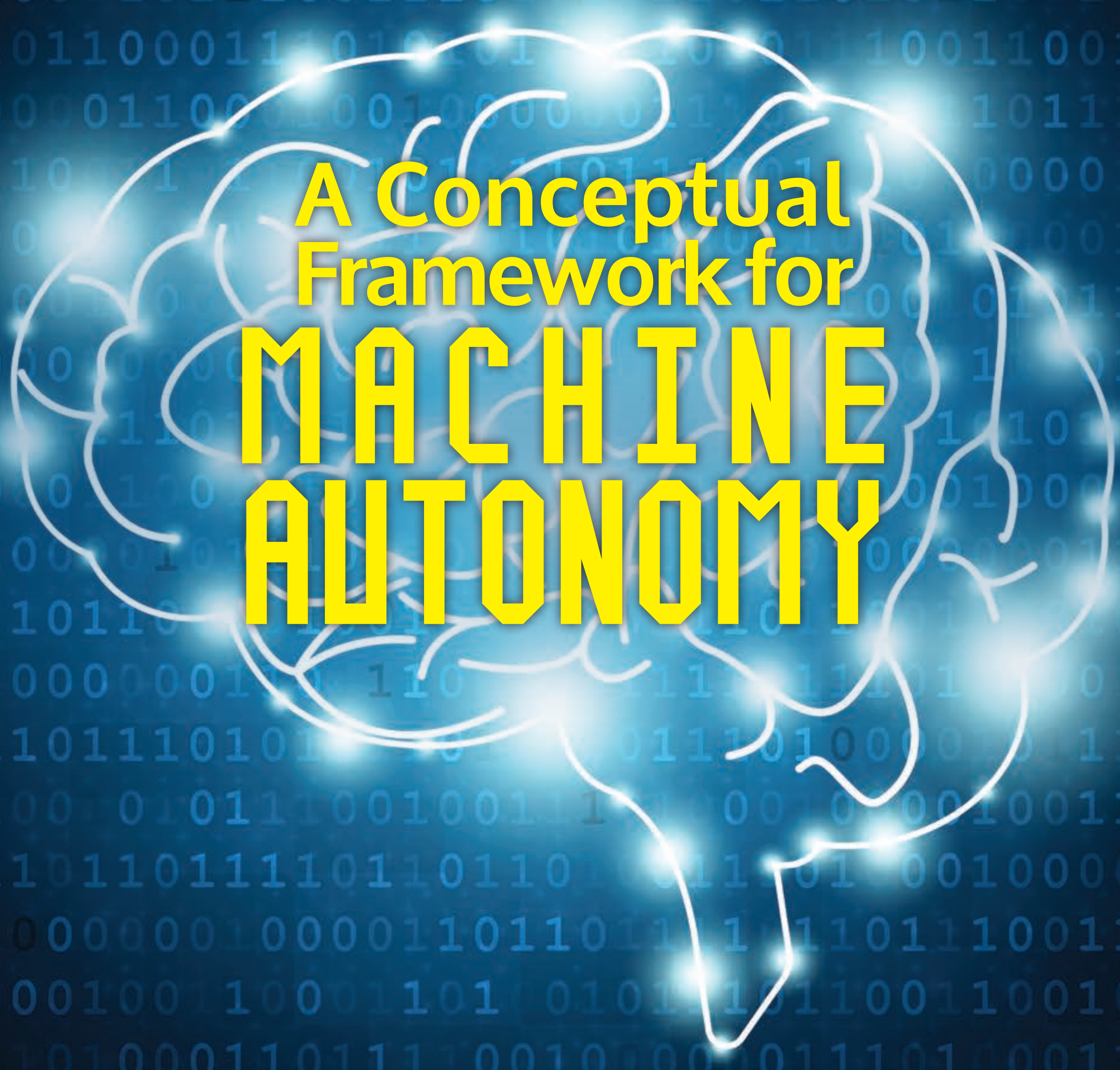
THE JOURNAL OF
AIR TRAFFIC CONTROL
OFFICIAL PUBLICATION OF THE AIR TRAFFIC CONTROL ASSOCIATION, INC.

Winter 2016 | VOLUME 58, NO. 4

A Conceptual Framework for MACHINE AUTONOMY



Plus

- Flight Planning and Weather Hazards
- NAV CANADA's Case Study
- A History of Terminal ATC
- FAA's Space Data Integrator

THE JOURNAL OF AIR TRAFFIC CONTROL
OFFICIAL PUBLICATION OF THE AIR TRAFFIC CONTROL ASSOCIATION, INC.

Winter 2016 | Vol. 58, No. 4

Published for:

Air Traffic Control Association
1101 King Street, Suite 300
Alexandria, VA 22314
Phone: 703-299-2430
Fax: 703-299-2437
info@atca.org
www.atca.org

Published by:

LESTER PUBLICATIONS, LLC

140 Broadway, 46th Floor
New York, NY 10005
Toll-free phone: 866-953-2189
Toll-free fax: 877-565-8557
www.lesterpublications.com

President, Jeff Lester
Publisher, Jill Harris

EDITORIAL

Editor, Andrew Harris

DESIGN & LAYOUT

Art Director, Myles O'Reilly
Senior Graphic Designer, John Lyttle

DIGITAL MEDIA

Digital Media Manager, Gayl Punzalan
Social Media, Jenina Bondoc

ADVERTISING

Quinn Bogusky | 888-953-2198
Tim Hothi | 866-953-2190
Walter Lytwyn | 866-953-2196
Louise Peterson | 866-953-2183
Darryl Sawchuck| 866-953-2193

Office Manager

Nikki Manalo | 866-953-2189

Printed in Canada. Please recycle where facilities exist.

Cover image: bannosuke / Shutterstock.com

Contents

ATCA members and subscribers have access to the online edition of *The Journal of Air Traffic Control*. Visit www.lesterfiles.com/pubs/ATCA Password: ATCAPubs (case sensitive).

Mikael Damkier / Shutterstock.com

Articles

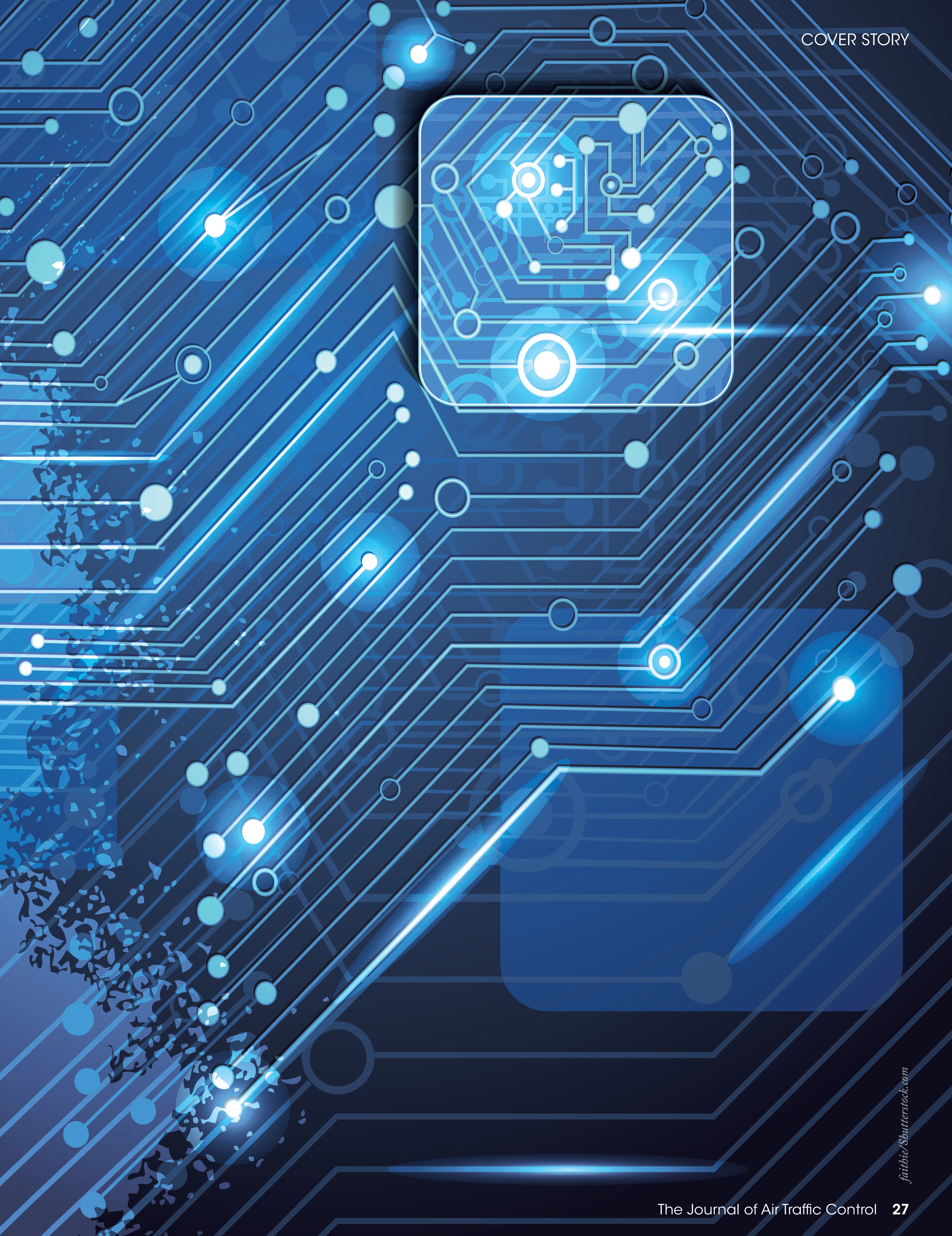
Departments

A Conceptual Framework for Machine Autonomy

By Liviu Nedelescu, Consultant

The mobility revolution of the last decade has forever altered our lives and transformed the transportation industry. Ever smaller, more robust, and more interconnected devices are embedding themselves into the very fabric of the human construct we call society. The future appears to no longer be about humans using technology; it is rather about seamless "techno-human" systems.

Aviation will not escape the implications of this 21st century disruptor, especially considering the rise of drones. Pervasive personal computing devices are enabling a celebration of individual choice and preference. Information and connectivity on demand have forever altered our collective expectations in terms of instant, personalized, customized experiences. This metatrend is generating new aviation business models that, arguably, exceed the moderate pace of innovation typical for this safety-critical field with a legacy of human-in-the-loop operations. As an example, behemoth companies such as Amazon and Pizza Hut want to see an air traffic system that accommodates point-to-point deliveries of goods. But the current air traffic management (ATM) governance model, together with its underlying hub-and-spoke architecture, was designed for mass transport. It is more or less obvious that assigning air traffic controllers to de-conflict the trajectories of drones delivering pizzas to neighborhoods is neither economically feasible nor scalable. A new buffer is needed to insulate the human operator from the foreseen exponential increase in both volume and complexity of air


faithie/Shutterstock.com

To deal with that which cannot be predicted, a machine must have the ability to both sense a deviation from the expected and learn to adapt.

traffic operations. If the future of the aviation industry is to echo the fundamental shift towards a personalization economy, autonomous flight technology needs to come into its own.

This article summarizes the intellectual efforts to frame the concept of autonomous machines such that distinguishing features can be gleaned, research challenges can be discerned, and an implementation path can be described. As such, the subject of autonomy is broader than aviation.

This article also aims to provide answers to questions such as:

- What distinguishes autonomy from automation?
- Does autonomy result from the natural evolution of automation, or does it require highly specific innovation leaps and focused, dedicated technology development?
- What are the changing roles of humans in an operational environment where autonomous machines operate?

Machine Autonomy: A Human-Centric, Evolutionary View

The highest-order attributes for human beings are arguably self-awareness and the tightly coupled notion of free will. Indeed, humans are autonomous beings. Replicating such traits in machines has long been the Holy Grail for scientists, philosophers, and fiction writers alike. Unconstrained by the limitations of what is currently feasible, science fiction has extensively explored the intellectual implications of the "singularity point" past which machines attain the ability (and volition) to self-improve. In fact, a favorite leitmotif of the genre is the double-edge sword that might characterize sentient machines – astonishing performance but also the distinct possibility of unthinkable risk. Opinions on how far current technology is from this envisioned theoretical limit vary widely. Nevertheless, sentient machines present a good conceptual terminus point for machine autonomy.

Figure 1 depicts a proposed four-step evolution highlighting the changing nature of human-machine interaction. Relevant initiatives that have already entered mainstream awareness are overlaid to the respective phases as pertinent examples lending credence to this otherwise notional path. Before discussing each step in more detail, it is important to note that the figure intends to convey an evolution that is non-incremental; that is, the proposed evolutionary steps are meant to suggest qualitative improvements worthy of paradigm shift status.

Era of Human-Machine Logic: Running on Von Neumann computing architectures, today's automation is wonderfully suited for outsourcing of routine, repeatable human tasks.[1] The human extracts logical commands from a larger context, which are then passed on to the machine in the form of "programs." Stripped of context, the automation requires human intervention whenever there are slight shifts in the environment in which it operates. This can hardly be called an autonomous state for machines. Even so, advanced automation is dramatically improving many aspects of human life.

Era of Human-Machine Reasoning: The convergence of global positioning systems, sophisticated sensors, and fast, low-power computing platforms is enabling machines to navigate physical environments. With the advent of technologies such as driverless cars, the temptation is to say we are entering a new era of machine autonomy. While machines will soon be able to *reason* with their surroundings without a human operator in the loop, they still lack awareness in the biological sense. Their responses to the environment they navigate are scripted. Once the operational environment exceeds the script, the "autonomous" driverless car stops and awaits human instructions. This next phase of human-machine reasoning is indeed a step forward towards machine autonomy. However, it is a very limited step. The limitations stem from the trivial belief that real world complexity can be neatly scripted to eliminate surprises. This belief favors brute force over true sentience.

Era of Human-Machine Cognition: As already alluded, humans have traditionally sought to simplify the environment in which a machine operates. Ensuring that machines encounter only a finite and pre-determined set of conditions to which they are prepared to respond is the very premise behind automation's reliability. Take a Google driverless car outside its mapped environment in California and insert it in a busy street in New Delhi, and it will simply sit there. Do the same with a dog, motivated by survival instincts, and it will seek to learn about its new environment. Biology still trumps machines in terms of autonomy. That is unless and until we are able to endow machines with biological-like cognitive abilities. Machines are already fitted with sensors that can inform them about their surrounding environment. What they are missing is the cognitive intelligence to make sense of environmental context, learn, and adapt new behaviors to accomplish a given intent. That is the basis of cutting edge research in new computing architectures that resemble the human brain. The hope is that a highly parallel architecture that no longer follows the distinct allocation of processing and memory in the Von Neumann sense may in fact be much better suited for contextual sense-making, environmental awareness, and learning.

Era of Human-Machine Consciousness: When machines are able to communicate with humans on the abstract level of value judgments, we will have achieved true machine sentience. This is also the theoretical terminus point for machine autonomy. A machine that

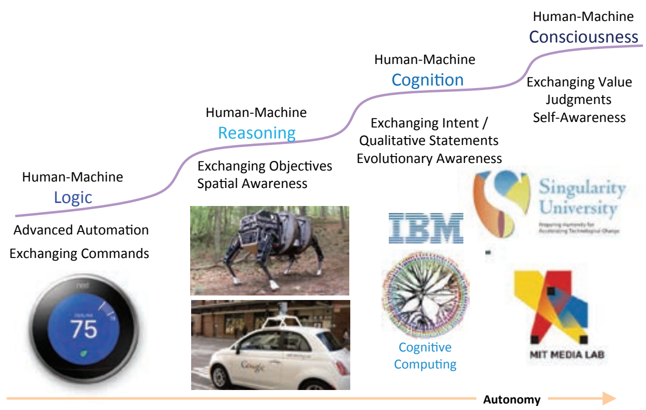


Figure 1. A proposed four-phase evolution for machine autonomy.

can qualify its own reasoning passes the self-awareness criteria and will be capable of autonomous tasks requiring first-order awareness and cognition. There is ongoing debate on whether this state will ever be reached. Futurists, like Ray Kurzweil, invoke Moore's law – the observed doubling of computing power every other year – to hypothesize computers that will eventually guide their own evolution and so surpass humans' ability to control them. Others disagree that computing power alone can result in machine sentience. Complexity biologist Stuart Kauffman argues that consciousness is not algorithmic and thus cannot be replicated by a Turing-based computing system.[3] He and others point to our current lack of understanding of the mechanisms of human consciousness – how can we design to emulate something we don't yet understand? The debate is likely to continue for quite a while. Fortunately, for most practical foreseeable purposes, it is difficult to imagine applications that would absolutely require machine consciousness.

The Autonomy-Complexity Correspondence

Why is autonomy necessary in the first place? Why doesn't advanced automation suffice? What, if any, is the difference between automation and autonomy? What theoretical basis, if any, is there to make a rigorous distinction between the two? A "complexity-autonomy" correspondence is vital to answering these questions.

Complexity is often invoked as a compelling argument for augmenting human abilities by way of technology. The typical pro-technology argument goes something like this: as complexity increases, it becomes more difficult for humans to maintain situational awareness, and the possibility of cognitive overload and mistakes rise. When pressed for the reason behind this assertion, few interlocutors are able to provide a definitive answer. That is understandable given that "complexity" is itself a loosely-defined term. A key notion of complexity is emergence – the formation of ad-hoc collective behaviors in systems with highly dynamic interactions. Emergent dynamics is a significant contributor to the argument for autonomous machines.

As long as a particular operational environment can be insulated from emergent dynamics, scripted algorithms such as those animating today's automation function effectively. This applies to many environments in which machines operate today, such as factory floors and warehouses. Taking a look at state-of-the-art transportation, both high-speed bullet trains and the proposed vacuum tube trains are examples of designers insulating automation from background complexity so as to ensure its effective and safe operation. A vacuum tube eliminates not only friction, but the possibility of any disturbance that might jeopardize a train moving at many hundreds of miles per hour. By contrast, autonomous drones in the airspace will encounter not only other autonomous drones, but, in the neighborhood delivery scenario, will also be immersed in the unpredictable and emergently complex world of human and animal life. A neighborhood with children, dogs, and workers on electric poles is a far cry from a vacuum tube in terms of complexity.

Those environments where highly interconnected networks of actors make open-ended decisions are *complex*. The key manifestation of complexity is precisely the possibility of emergent conditions, i.e. those outcomes that cannot be predicted. The global economy is just such an environment, and the financial crisis of 2008 provides a pertinent case in point. Social media and the emergent phenomenon of "going viral" is perhaps an even more familiar illustration. An ATM example is afforded by Traffic Flow Management. Traffic managers are still experimenting with various exit strategies for how to shut down a Ground Delay Program (GDP) in a way that avoids traffic build-up. The post-GDP traffic build-up is an emergent phenomenon arising from the interaction of traffic flow practices with airlines' business rules.

Automation running scripted algorithms designed to address pre-defined conditions runs into logical inconsistencies when facing the emergent and the unforeseen. To deal with that which cannot be predicted, a machine must have an ability to both sense a deviation from the expected and learn to adapt. This ability distinguishes autonomy from automation. In other words, machine autonomy is required in environments complex enough to allow for emergent conditions, hence the autonomy-complexity correspondence. It is complexity that drives the need for autonomy.

Emergence draws a clear delineation between automation and autonomy. For a piece of automation to pass the "autonomy" test, it must demonstrate it can handle emergent conditions on its own.

Safety and Technology Considerations

If one can prove that autonomous machines will always behave within pre-defined parameters, then they are not truly autonomous. If one allows for autonomous machines, then they cannot prove they will operate within pre-established parameters.

The Notion of Trust: This proposed paradox is generated by the clash of current deterministic methods with the envisioned non-deterministic traits of autonomous technology. The very words used to describe traditional safety techniques, such as "verification," seem utterly unsuited for machines adapting to emergent environments. This scenario assumes that, through studying its design, engineers will understand all possible states and behaviors of a machine, and engineers can therefore test and validate prior to operation. Autonomy needs to accommodate the possibility of a machine developing new behaviors *while in operation*. In the case of autonomy, the human-machine safety relationship is not a simple one-directional and one-time post design event. It is rather a two-way, reflexive coordination that happens continuously, in operation. Learning requires memory and temporal directionality. As machines learn, the history of the process needs to be considered such that a certain novel behavior is fully understood and appreciated *in context*. In essence, autonomy demands a much more organic relationship between human and machine where trust, gradually built over time, results in safety.

Contextual Machine Learning Technology: Learning appears to be the prerequisite for delegating authority to machines that may

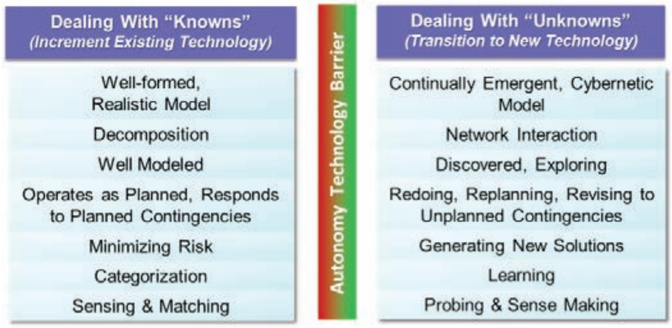


Figure 2. The technological barrier for autonomy.

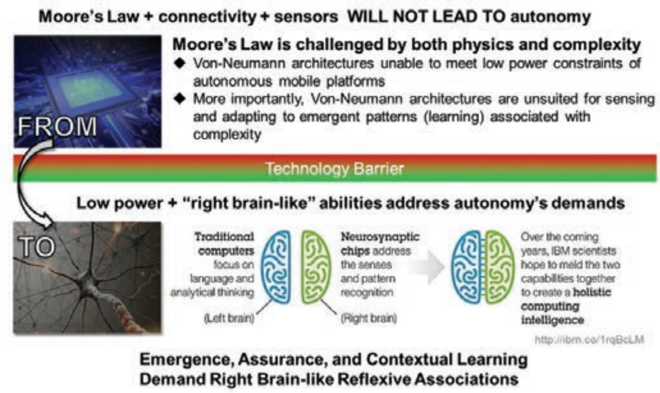


Figure 3. "Right-Brain" computing architectures offer possible explanation for machine autonomy needs.

face emergent conditions. The concept of trust is also intricately tied to the machines' ability to learn. Machine learning is an active field of research. However, most current machine learning technologies are not well suited for discerning contextual subtleties. For example, machines have a difficult if not impossible time dealing with the question that most five-year-olds find trivial: "what seems out of place and doesn't belong in this picture?" Current machine reasoning is limited to "if-then" type look-up tables that match previously observed environmental conditions to suitable actions. The question of something being out of place does not identify an observed condition, and so the machine has no starting point from which to compute. This type of question of "open-ended" observation is however essential for machines intended to operate in human-dominated environments, such as suburban neighborhoods where drones might soon deliver pizzas. And so, arguably the most important element of learning technology for autonomous machines is the contextual trigger – identifying the out-of-place that isn't contained in the machine pre-programmed look-up algorithm.

As illustrated by Figure 2, contextual sense-making continues to constitute a veritable technological barrier.

A reliable technology to address this challenge has yet to be developed. Current Von Neumann-based computing architectures are great at fast execution of scripted algorithms, but they are poor at contextual sense-making and learning. As presented in Figure 3 below, Von Neumann Architectures are good at "left-brain" analytical processing; they are poor at "right-brain" contextual sense-making. A number of organizations, including IBM, ARM, DARPA, and HP, are actively looking to develop new computing architectures that more closely resemble organic brains. These organizations hope that the highly parallel neurosynaptic computing architectures will provide a leap in terms of performance with tasks usually attributed to human cognition like pattern recognition, anomaly detection, etc.

Safety and Non-Determinism: Having established the notions of emergence and trust, and their respective correspondence to non-determinist methods, a new question emerges: is safety even an achievable goal in a non-deterministic environment? The answer is affirmative. We also believe that achieving a positive result rests with the design of a governance model whereby enough resources – principally time – are afforded to the machine such that it hones in on behaviors that lead to valid outcomes. It is important to stress that establishing trust in an autonomous machine should be biased towards the end objective rather than the means. Autonomous machine trust concepts must allow for a variation of means by which a machine achieves a valid outcome. The particular solution an autonomous machine might choose to satisfy a particular objective might contain an element of surprise; the outcome should not.

Converging Autonomy Threads Into a Cohesive Framework

The complexity notion of emergence becomes the foundational concept framing autonomous machine technology. While trust and contextual machine learning can each be derived from the emergence theory, they are sufficiently important to be instantiated as stand-alone autonomy items of interest. Figure 4 illustrates the convergence of emergence, trust, and contextual machine learning into a robust framework to form a research strategy for developing machine autonomy technology.

As depicted in Figure 4, for a machine to be deemed "autonomous," it has to both acknowledge and engage emergent phenomena as they arise out of complex environments. From the safety point of view, autonomous systems are likely to expand the traditional focus on means to outcomes. True adaptive artificial intelligence appears to require computing architectures that emulate biological ones. These architectures will become available in the coming years.

Useful Conceptual Instruments

There are a number of conceptual instruments that can be useful in limiting the temptation to ascribe deterministic methods, language, and concepts to machine autonomy.

When dealing with notions at the edge of knowledge, definitions can be hard to pin down. Experts apply jargon that is subject-matter-specific depending on their point of view. Rather than prematurely attempting surgically precise definitions for the notions of emergence, trust, and contextual machine learning, a more practical means might be in order. Below are several "challenge statements" meant to stimulate constructive dialogue around the notions of emergence and trust.

Emergence challenge statements:

- Autonomy is the recognition of the need to react when detecting emergent behavior. It is not about solving problems in emergent environments; it is about the ability to sense the approach of an agent's own performance boundaries and invoke new resources.
- Autonomous machines require the ability to interpret the part of reality that falls outside statistical correlation – clustering, pattern recognition, and the like.
- If the operational environment is confined to non-emergent behavior, systems engineering-based automation is adequate. Otherwise, "beyond-automation technology," i.e. autonomy, is needed.
- The ability to deal with context is an intrinsic function of autonomy. Context is defined as a condition inside or outside of a

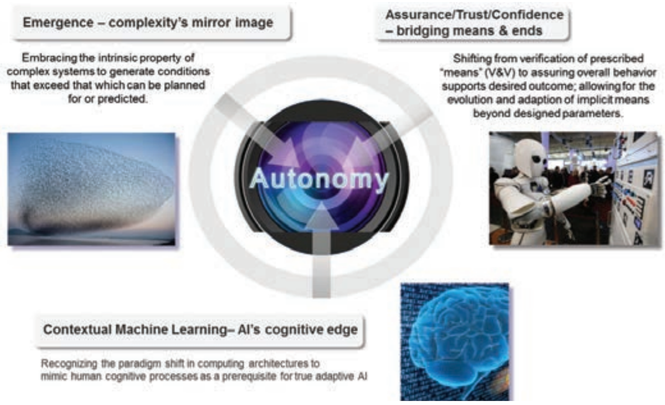


Figure 4. Emergence-Trust-Contextual Machine Learning: a robust machine autonomy framework.

boundary; it is therefore both relative and fluid.

- Autonomy-limiting factors are dependent upon context, behavior, object, and better understanding our tolerance for those factors.

Trust challenge statements:

- Trust, in terms of autonomous system operation, requires a paradigm shift in validation and verification from an "all-or-none" design activity to a more agile and continuous operations activity; this results in less "overhead" and implies "elastic" performance boundaries.
- Trust, in the context of autonomy, means that a system is able to monitor its own performance.
- Governance of autonomous systems must be capable of inserting adaptive technology in a fluid environment.
- Varying activity "tempo" is a major technical challenge for machines emulating humans.

Applying the Autonomy Framework to Expose Automation Bias

The proposed framework is a robust autonomy tool. It adds a measure of conceptual rigorousness in a nascent field where there are few conceptual navigational aids. For example, the Google driverless car is portrayed by many media articles as an example of "autonomous" technology. And yet, Google's technology doesn't pass the emergence test. Its environmental awareness intelligence is limited to look-up table technology. It is only as smart as its scripted algorithms. Change its context, for example, moving it from San Francisco to New Delhi, and it will not function. It will not engage the new context via a learning process. It will not on its own attempt to adapt. Therefore, from the perspective of the proposed autonomy framework, the Google driverless car, while exceptionally advanced, firmly fits the automation categorization. Says Professor David Mindell of Massachusetts Institute of Technology's Department of Aeronautics and Astronautics and of Humatics Inc. regarding self-driving cars:

> "There's an idea that progress in robotics leads to full autonomy. That may be a valuable idea to guide research … but when automated and autonomous systems get into the real world, that's not the direction they head. We need to rethink the notion of progress, not as progress toward full autonomy, but as progress toward trusted, transparent, reliable, safe autonomy that is fully interactive: The car does what I want it to do, and only when I want it to do it."[4]

What's Next?

The machine autonomy framework presented is anchored in complexity thinking. Emergence is used as the relevant complexity manifestation. This fascinating phenomenon is actively studied in several formal disciplines – complexity science, network theory, resilience engineering, and cybernetics, to name a few. Together, these active inquiry efforts can provide ample insight into fundamental mechanisms that drive emergence. Feedback loops and weak signals are two such examples. Making these mechanisms and their relationship to emergence explicit will provide a wealth of solid formalism that can be used to anchor research and technology development plans. Taking the extra step in terms of instantiating an explicit traceability between complexity mechanisms and machine autonomy is a necessary and sufficient next phase for framing an autonomy research agenda. Engaging the various communities of practice, mainly those focused on the complexity science and next generation neurosynaptic computing architectures, is a necessary next step.

Machine autonomy is not just one of many alternatives to a future airspace; it is the key for instantiating new operating paradigms. Scale operations that justify the economic case for new applications such as drone deliveries cannot be achieved but for autonomous flight. It is therefore important for the aviation community to acknowledge autonomy as the true desired end-state of a future national airspace where drone applications are fully exploited. Reaping the low hanging fruit yielded by advanced automation with humans-in-the-loop is fine in the near term. Such early drone integration successes should however not be decoupled from the larger context of the "true-north" endeavor of autonomous flight.

Liviu Nedelescu is a subject matter expert who has, for over 15 years, spearheaded efforts to frame intractable airspace problems using systems thinking formalism. Nedelescu has consistently argued the NAS is best framed as a complex-adaptive system. He has proposed that a full understanding of airspace operations requires expanding the classical systems engineering mindset with new complexity-aligned methods. Nedelescu is with MCR Federal, LLC supporting Civil Manned and Unmanned Aviation efforts.

References

[1.] *A computer architecture described in 1945 by the mathematician and physicist John von Neumann and others in the first draft of an EDVAC report. The principal feature of a von Neumann computer is that the program and any data are both stored together, usually in a slow-to-access storage medium such as a hard disk, and transferred to a faster, more volatile storage medium (RAM) for execution or processing by a central processing unit. Since this is how practically all present-day computers work, the term "von Neumann architecture" is rarely used anymore. This describes a design architecture for an electronic digital computer with parts consisting of a processing unit containing an arithmetic logic unit and processor registers, a control unit containing an instruction register and program counter, a memory to store both data and instructions, external mass storage, and input and output mechanisms.*

[2.] *The main drawback for von Neumann-based computing architectures is they carry out instructions one after another, in a single linear sequence. This problem is called the "von Neumann bottleneck." Parallel processing can alleviate this problem, but such modifications don't really amount to much more than variations of the original architecture.*

[3.] *A Turing machine is a mathematical model of a computing machine that can use a predefined set of rules to determine a result from a set of input variables. Kauffman argues Turing machines are deterministic in nature, while human consciousness is not. For a more detailed explanation see Kauffman S., "Answering Descartes: Beyond Turing", MIT Press.*

[4.] *From MIT News, October 13, 2015*