SEPTEMBER 2019

AUTONOMY AT SCALE

Intelligent Machines Advancing Technology to Improve our Future

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INTRODUCTION

Karl Wunderlich

Autonomous machines are by definition capable of performing tasks without human interaction. They may also be mobile, that is, possess the ability to explore their immediate environment while fulfilling assigned tasks. An emerging set of new autonomous, mobile machines—either deployed operationally or in development—are poised to augment, transform, or disrupt current forms of human activity in a wide range of physical environments and use cases, as illustrated in Figure 1.

On the sea surface and in the undersea environment, a team of autonomous submersible vehicles search a sector of sea floor in coordination with command and control machines located on and below the ocean surface.

On the land surface and near-surface environment, automated wheeled and airborne vehicles transport travelers and goods in a urban environment without intervention from human drivers or remote pilots.

In higher altitude airspace, fully or partially automated aircraft carry passengers and freight and perform surface reconnaissance and other missions by maintaining safe flight paths in coordination with space launch vehicles passing through to deliver other machines into orbit.

Outside of Earth's atmosphere, machines placed into terrestrial or extraterrestrial orbit support a range of autonomous landers and rovers deployed onto extraterrestrial surfaces.

Figure 1: Autonomous, mobile machines at scale are poised to transform human activity in a wide range of physical environments.

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While autonomous machines have been the subject of intense public interest, this interest has focused on the potential of individual or isolated autonomous machines (e.g., the advent of a partially or fully automated "driverless" vehicle).

Far more powerful, however, is the potential of systems of multiple, connected, mobile autonomous machines-machines that in concert can tackle complex problems no single machine, no matter how well designed, can manage in isolation.

Much as the human experience has been one of social collaboration to achieve long-sought capabilities, the power of many autonomous machines dwarf the potential impact of any single machine. While humans can draw from a millennia of shared experience and collaboration to organize their actions, autonomous machines have inherited only a blank slate at worst, or at best, an imitation of human interaction to draw on for inspiration.

Achieving autonomy at scale means getting large systems of systems to work seamlessly and efficiently. This outcome is far from certain, however, without a strategy for mobilizing and orchestrating autonomous systems to be both self-organizing and interoperable, the vision of transformative impacts becomes less distinct and less valuable (Figure 2). Pockets of purpose-built autonomous machines working specific shared use cases may still provide new capability and intrigue the public. However, such a limited future of Autonomy at Scale pales in comparison to the potential unleashed by millions of heterogenous autonomous machines operating in and among a multitude of (potentially concurrent) use-cases, adapting in real-time to new tasks while simultaneously balancing competing demands.

Figure 2: Without the ability to self-organize and inter-operate, the impact of autonomy at scale will be significantly reduced.

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Autonomous Systems – Autonomy at Scale Defined

Autonomy at Scale (AaS) encompasses a wide variety of emerging capabilities in the civilian and military spheres. Figure 3 illustrates their key attributes:

- **Multiple, Heterogenous Machines** — Machines differ in size, capability, mobility, sensing and compute power. Each machine may be configured to complete a specific sub-task associated with system objectives.
- **Connected (wirelessly)** — Wireless connection enables coordination and information sharing. Note that communications may not be ubiquitous and that some machines may spend time outside of communication range.
- **Self-Organizing** — The system of machines is capable of some level of independent adaptation to events in their environment without direct human intervention. This self-organizing capability augments one or more human controllers who set higher level objectives for the system.

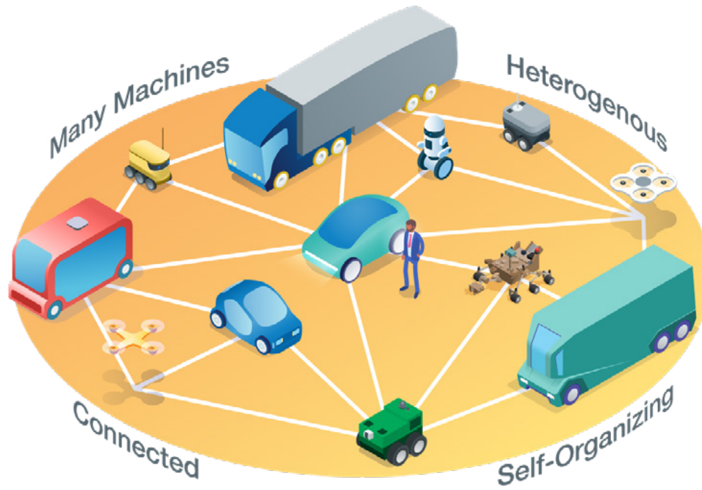

Figure 3: Attributes of autonomous systems at scale.

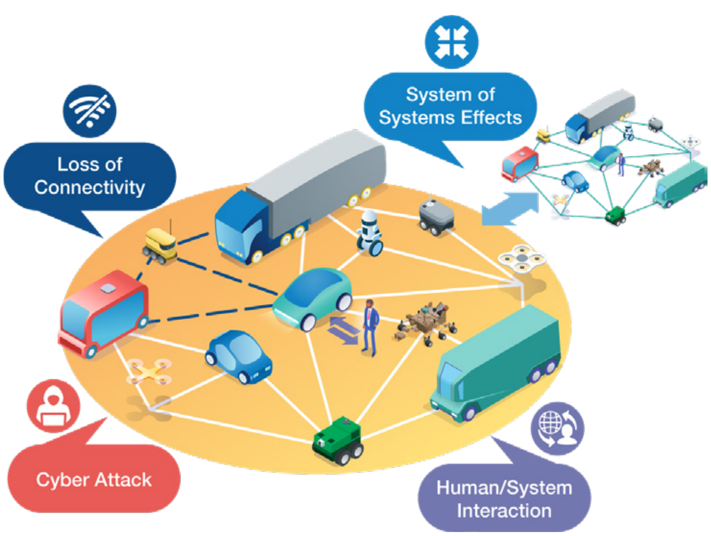

Figure 4: Challenges to large autonomous systems.

Challenges to Autonomy at Scale

Figure 4 illustrates key challenges in large scale autonomous systems:

- **Loss of Connectivity** — Natural or other forces may cause some or all machines to become isolated.
- **Cyber Attack** — A malicious actor may exploit or even suborn the system, possibly using only a single machine as an attack surface.
- **System of Systems Effects** — Systems will have to interact with neighboring systems with different capabilities and objectives.
- **Human/System Interaction** — The complexity of the autonomous system may be difficult for the human controller. The number of potential events and future system states makes comprehensive training impossible.

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PURPOSE OF THIS DOCUMENT

This document explores the promise, costs, and challenges associated with emerging massive-scale systems of autonomous machines in key domains and use cases.

Autonomous machines are poised to transform the way we travel, distribute, and deliver goods and how we explore, manage and monitor the sea, surface, air, space, and extra-terrestrial environment. Most of the focus on autonomy has been on isolated autonomous machines - that is, vehicles (sea, land, air, space) that can plan motion paths, navigate around obstacles and perform tasks without human control or oversight. These individual machines are technological marvels, combining arrays of inexpensive but powerful local sensor systems, machine learning, and complex control systems; however, the outcomes associated with deploying these autonomous machines at scale, in the millions, are not clear. Will systems of autonomous machines at scale be safer? More efficient? More secure?

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Organization of this Document

A collection of subject matter experts and thought leaders from the Noblis enterprise have contributed their viewpoints to these questions.

First, we present an overview of the four fundamental technologies that form the foundation for the advent of autonomous systems at scale:

- **Sensor Systems** — James Chang summarizes the revolution in sensor technologies that has enabled a new wave of low-cost, high-resolution sensor systems to be integrated into autonomous mobile machines.
- **Position, Navigation, and Timing** — Matt Monaco summarizes the state of supporting technologies that allow autonomous machines to estimate their absolute positions, navigate terrain, and share a common sense of timing with surrounding machines.
- **Sensor Fusion and Machine Learning** — Sterling Thomas examines the quantum leap in integrating diverse sensory inputs and creating plans of action for autonomous machines, made possible by advances in machine learning.
- **Connectivity** — Keith Biesecker provides a cross-section of the technologies that allow machines to connect and communicate across the wide range of potential environments.

Next, we provide a deeper dive into specific environments and explore use cases for autonomy and autonomous systems:

- **Surface Transportation** — Karl Wunderlich examines the advent of automated vehicles, their promise and challenges.
- **Air Transportation** — Matt Monaco describes the state of autonomous aircraft from small drones to large high-altitude platforms to examine the potential challenges in an airspace crowded with autonomous and piloted vehicles.
- **Space** — Darin Skelly looks at the emerging opportunities for autonomous systems in Earth's orbit, in the extraterrestrial orbit, and on the extraterrestrial surface.
- **Adversarial Environments** — Daniel Yim and Thomas Mitchell characterize the current state of autonomy in warfighting and other adversarial environments and the potential for massive scale autonomous systems.

In our last section we examine two cross-cutting issues related to the challenges of realizing autonomous systems at scale:

- **Ensuring Interoperability Among Autonomous Systems** — Mile Corrigan examines what steps can be taken now to help transition individual autonomous systems into an effective system of systems to meet critical objectives.
- **Cybersecurity** — Sam Leetsma characterizes the threats and potential actions to be taken to secure massive-scale autonomous systems from cyber attack.

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