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AUTONOMY AT SCALE

Intelligent Machines Advancing Technology to Improve our Future

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FUNDAMENTAL TECHNOLOGY: **A PRIMER ON SENSORS**

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Just as human senses guide our every move, sensors, and sensor subsystems are a fundamental building block for how autonomous systems are designed and operated, and represent a key driving force as autonomy moves to scale. Sensors provide the basis for autonomous decision-making. They collect all localized inputs, whether through on-board sensors, a combination of sensors and processing (sensor subsystems), or communications with other sensor systems (including sensor fusion) leveraging connectivity with autonomous peers, as illustrated in Figure 1. The evolution of sensors has accelerated in leaps and bounds to not only exceed human ability—even enabling uses where it has shielded humans from high-risk environments—but also to develop in areas where no human equivalent exists. The processing components have also kept pace and can now extend sensing capability beyond quantitative inputs. For autonomous systems, onboard sensing capabilities are anticipated to remain a key function that drives overall capability—even as more sophisticated communications-based approaches allow for sharing of information from external sources.

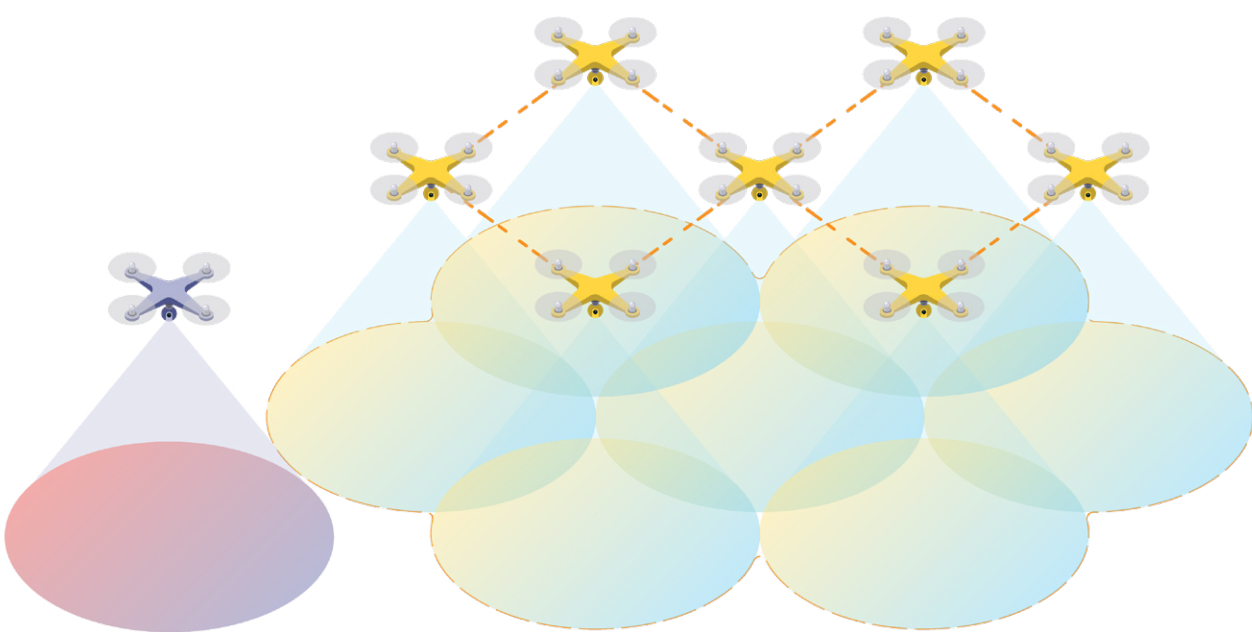

Figure 1: "Collective vs. individual perception." AaS leverages communications to share sensor data.

Fundamentals at Scale: Cost as a Key Driver

Fundamentally, sensors gather data from the physical environment and convert it into a quantitative form. The application of a given sensor is defined by its purpose within the autonomous system, but there can be a variety of sensor solutions that can contribute to an application. Design decisions are made based on sensor characteristics and attributes as well as cost. As in other industries, cost has proven to be a primary determinant at large scale—both in terms of defining the envelope of commercial feasibility and influencing the cost of sensor components. Continuous innovation in parallel technological industries has a great influence on development and costs, such as in the example of the evolution of digital camera sensors used in autonomy which leveraged the cell phone/smartphone market. In the fourth quarter of 2018, worldwide smartphone sales topped 400 million units[1], meaning that components were manufactured in volumes allowing engineering costs to be widely amortized. This allowed unit costs to be comparatively low for a sensor that would not have been imaginable outside an expensive specialty market only a decade earlier. Supporting this cost trend, the manufacturing process itself continues to become increasingly automated, which has lowered the labor component of unit costs.

Common Sensor Types used in Autonomous Systems

Basic sensor suites, available at a low cost, and offering relatively simple autonomous capabilities - can be deployed efficiently. The basic sensor building blocks needed to support local orientation and movement may vary by environment (e.g., ground vs. air) and use-case domain (e.g., rover detecting physical obstacles by force feedback vs. autonomous vehicle sensing movement of surrounding vehicles while moving at highway speeds). The purpose and application domain of an autonomous system will impact its need for and use of onboard sensors. For example, an autonomous system's speed and operating environment will influence sensor range requirements for obstacle detection: an ultrasonic sensor requires a compatible medium to transmit/receive sound waves and the deep-sea environment requires sensors capable of withstanding high water pressure. On a small, lightweight unmanned aerial vehicle (UAV), weight factors may influence a design to utilize processing of sensors to extract additional input, rather than separate self-contained sensors.

EVOLUTION OF LIDAR SENSORS FOR AUTOMATED VEHICLES

LIDAR sensors for the automated vehicle (AV) market have progressed from large, bulky research equipment atop test vehicles to small, low-profile units suitable for early AV markets in operational settings, such as pilot robo-taxi fleets. Research continues toward a solid-state implementation of LIDAR sensors—anticipated to be less expensive to manufacture[2] as they leverage the semiconductor manufacturing process to achieve scale. Should these advancements help LIDAR move significantly lower on the cost curve, they may be adopted much more widely in autonomous systems that operate at scale.

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In some cases, sensor outputs may be utilized for multiple purposes. A camera sensor used to detect lanes for autonomous driving could also provide a source of image data to relay to back-office systems for data collection (e.g., roadway infrastructure and signage). Taking this concept to its furthest point, simultaneous localization and mapping (SLAM) allows sensor inputs to be used to establish a mobile autonomous system's location relative to its environment while at the same time collecting data to build and enhance an internal model of the environment itself.

SELECTED EXAMPLES OF SENSOR TYPES RELEVANT TO AUTONOMY

Sensor Type Examples	Use as Basic Building Block	Domain Specific Application
Accelerometer	Orientation of autonomous unit	Measuring external shocks (e.g., pothole)
Acoustic (e.g., ultrasonic, sonar)	Detect proximity or range of nearby objects	Precision self-parking/ docking of autonomous vehicle
Radar	Detect speed and relative position of vehicles and obstacles ahead	Detect and track offensive projectiles
Infrared (IR)	Detect and distinguish objects in limited lighting or which have characteristic signatures	Heat (human/animal) detection/tracking
Optical Camera	Visual tracking of lane markers, detection of obstacles under favorable visibility conditions	Photographic survey of target (e.g., bridge superstructure, electrical transmission tower) being monitored
LIDAR (Light Detection and Ranging)	Localization with respect to stored reference map or SLAM, detailed obstacle classification	Georeferencing physical inventory of objects of interest

Sensors at Large Scale

For autonomy at large scale, sensor costs may be affected by the specific autonomy market. For example, if a nation-state regularly purchased millions of consumable single-use drones, the underlying unit costs of sensor components could be driven lower through economies of scale. As in the mass marketization of technology products with higher unit volume orders, the sustained nature of production, as opposed to start-stop production and re-tooling, influences the realized unit costs, as illustrated in Figure 2. As such, there are likely to be a few domain-specific exceptions.

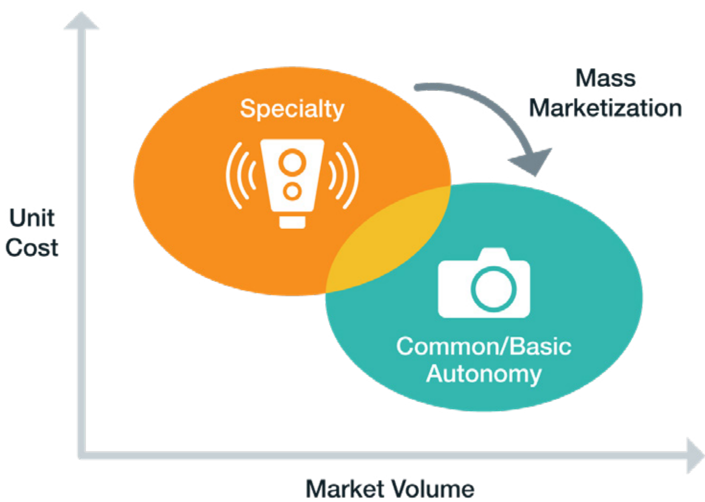

Figure 2: Mass markets have facilitated availability of low-cost building blocks for autonomy

Autonomy at scale will rely heavily on sensor building blocks that are already produced at scale or in adjacent markets such as smartphones that continue to bring evolving technology components—smaller, lighter, lower power—at high volume to the marketplace, as illustrated in Figure 3.

When sensor scale is achieved, opportunities resulting from the data they collect will be unlocked. In aggregate, sensor data collected by autonomy at scale may provide the basis for machine learning and big data analyses that individual autonomous systems alone could not support.

Future markets are not simply continuations of the current market; what is ubiquitous today may be overtaken by new and unknown technologies and products of the future. Likewise, the sensor technologies and manufacture processes themselves are subject to technological and business innovation, which can affect the material and manufacture costs of sensor components. For example, if a sensor relies on materials in constrained supply, such as rare-earth elements, new sensor technology could offer lower-cost alternatives. On the other hand, geopolitical factors could also artificially limit supply of elements causing prices to rise. Multiple competing approaches (e.g., use of cameras and radar vs. LIDAR in autonomous vehicles) may also affect the future outcome as market forces influence the production volumes of the underlying sensors.

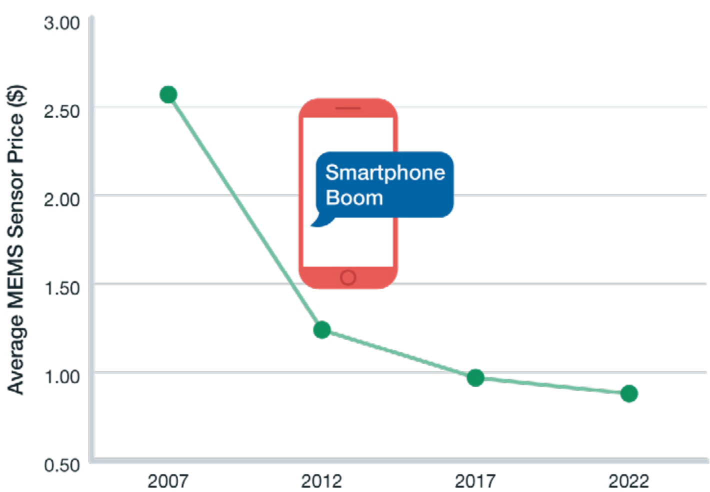

Figure 3: Prices of MEMS (Micro Electronic Mechanical Systems) sensors (e.g., accelerometers) have benefited from semiconductor technology trends[3].

Domain-Specific Sensors at (Lesser) Scale

Even at a lesser scale, autonomy changes the paradigm to allow design cost flexibility for domain-specific sensing systems that have a greater level of sophistication, technology, and potential for labor-intensive or material-intensive production. Sensors at lesser scale may also reflect an emerging market, where manufacturers develop sensors anticipated to permit an autonomous system market to scale up. For example, the promise of an environment with millions of autonomous vehicles may be envisioned in the future but does not exist today. Sensor developers nonetheless have been producing relatively high-cost LIDAR systems for the research and development (R&D) and high-utilization AV market today while continuing development toward viable mass-market solutions.

In other cases, a large-scale marketplace may not be anticipated due to the narrow specialty (e.g., chemical, biological, radiological, nuclear, and explosive (CBRNE)). R&D in this space will likely yield incremental improvements in sensor capability and performance, which are often of primary concern. These kinds of particular use cases where substitutes are not available or suitable often require specialty sensors. For example, CBRNE detection and characterization may utilize onboard sensors that sample the surrounding air for analysis in real-time. While basic sensors such as cameras may be used as a supplement, specialty sensors like those for the CBRNE domain will be less likely to have cross-domain applications.

Sensor Reliability and Security

Depending on the domain, confidentiality, integrity, and availability of sensor systems may be significant design requirements. For autonomous systems that operate in adversarial or hostile environments, sensors may be designed to resist interference or secure/encrypt data collected and transmitted. Even in a commercial context, where raw data from sensors is often unsecured, autonomous systems need to consider the level of reliability and mechanisms to monitor sensor performance and health—particularly for critical sensors or applications. For applications where formal analysis to justify policies (e.g., operation beyond visual line of sight) are required, the reliability of the underlying sensors are key components. Yet the risks of adversarial attacks on common commercial sensors like cameras/image processing systems may not be accurately captured in traditional safety and reliability analyses. Other issues, such as sensors' mutual interference, may not be evident except at scale. Failure to manage sensor reliability at scale can contribute to widespread vulnerability to external threats, whether adversarial or environmental. To the extent that the environment can be constrained (limiting the scope of design domain), achieving sufficient reliability could be more manageable. However, the failure to adequately consider the environment could make an otherwise highly reliable sensor system vulnerable to blind spots.

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Tradeoffs of Scale

What is better: many less-sophisticated autonomous units or a few advanced units? The environment may be the deciding factor. In hazardous or extreme environments, the functional performance characteristics of commercial low-cost sensors operating beyond their design domain may negate the suitability for an application or could be accepted as a tradeoff for limited situations. For domains where autonomous mobile systems must operate in harsh conditions, more stringent requirements may necessitate the use of specially designed sensors and/or supplemental components to protect the underlying sensor. Depending on the specific sensor characteristics, some limited functionality may be possible and the tradeoffs may be acceptable when factors such as availability, costs, and feasibility are considered. Sensors subject to extreme temperatures and the physical shock experienced in space travel or harsh earth environments (e.g., deep sea, desert, arctic, geothermal, low atmosphere) may also be subject to similar tradeoffs. Autonomy at a large scale raises the possibility of a "disposable" autonomous system, where limited sophistication but significantly lower cost to be expendable, may present an acceptable tradeoff[4].

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The use of a large number of autonomous systems and their corresponding sensors can bring additional complexity as well as opportunities and threats. Communication across multiple autonomous systems with independent sensors, either in real-time or in back-office systems, can yield potential redundancy for reliability and more detailed measurements than a single sensor. These benefits can enable the application of techniques such as machine learning or advanced post-processing. Multiple levels of intelligence from sensors can be achieved—local (tree) vs. sensor fusion (grove) vs. collective processing (forest)—where the overall value has the potential to be greater than the sum of the parts. In some scenarios, the ability to perform computations at scale may be more efficient than improving individual sensors. The communication and management of the significant quantity of data will present a challenge in itself—especially as autonomy moves to a larger scale, or where the environment impedes communications or latency affects the performance.

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