Bringing Autonomy to Industrial Control Systems

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Microsoft

Contents

Engineers are designing increasingly intelligent industrial machines

Across every industrial sector, dynamic and intuitive machines are changing how businesses operate. Unlike traditional rules-based technology, these flexible machines and processes adapt to dynamic environments and changing variables. Imagine a production line where robotic arms install electrical components in machines. Typically, the arm would have to pause if a part wasn't oriented correctly on the production line. But with dynamic, adaptable technology, the arm can adjust its movement to easily install the part no matter how it's positioned.

This isn't technology from some distant future. From drones that inspect pipelines independently to self-optimizing greenhouses, there are countless examples of intelligent technologies impacting the world today. Just as steam and electricity revolutionized industry a century ago, AI-based technology is fueling the fourth industrial revolution, or Industry 4.0.

17-20%
productivity gains realized by manufacturers that implement intelligent systems[2]

Industry 4.0 is built on intelligent, connected systems

Industry 4.0 is defined by the infusion of intelligence, connectivity, and automation into the physical world. Smart, connected, and agile operations are ushering in a new era of digital industry. Beyond just technology, this means connected end-to-end ecosystems, innovative business strategies, and productive, empowered employees. And like previous industrial transformations, Industry 4.0 has the potential to create a massive amount of value for nearly every organization, generating up to $3.7 trillion by 2025.[1] To cite numbers more applicable to average businesses: 50% of companies that embrace AI over the next 5 – 7 years may double their cash flow. And manufacturers that implement intelligent systems achieve 17 – 20% productivity gains.[2] These shifts represent a remarkable opportunity to innovate and carve out distinct competitive advantages.

The potential of Industry 4.0 is enormous. But what does the transformation entail?

The roadmap to Industry 4.0

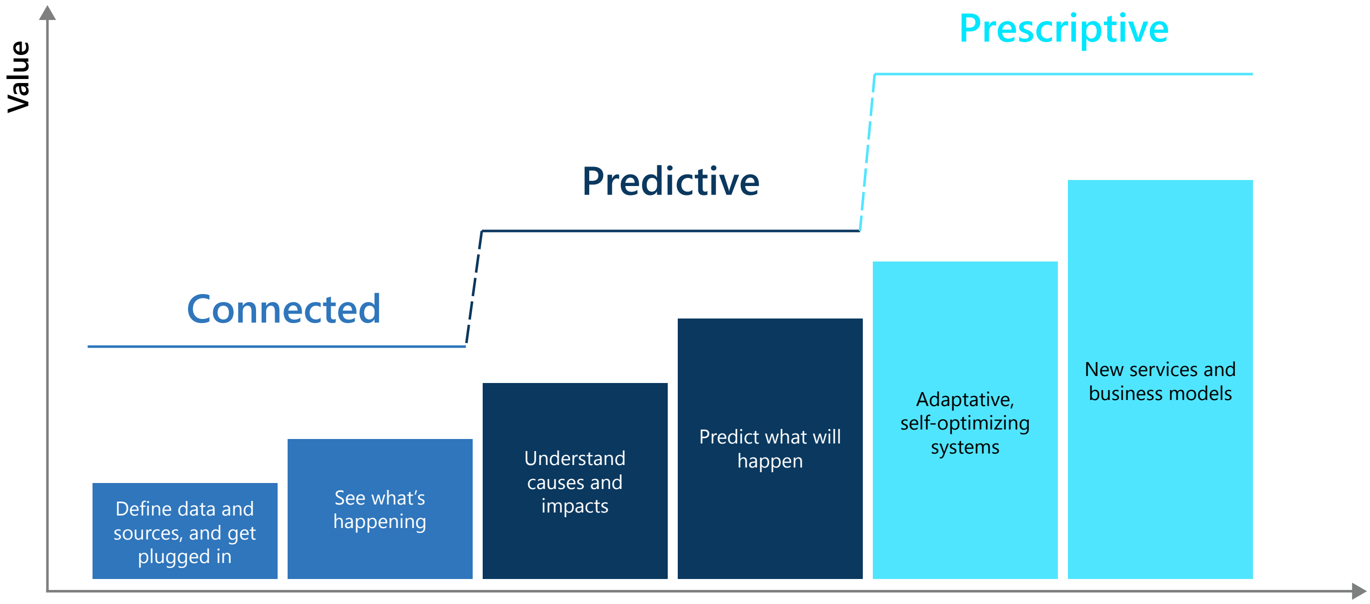


Figure 1. Levels of intelligence in Industry 4.0.

At Microsoft, we've helped organizations across every industry achieve digital transformation and realize the promise of Industry 4.0. Above, we've outlined the typical progression that we've seen these customers take.

- Many manufacturers are currently at the "connected" level: establishing connectivity between machines, production lines, and control systems.
- At the "predictive" level, organizations leverage IoT data to gain a greater understanding of their operations and use machine learning to predict what will happen, like when a machine will need maintenance.
- At the "prescriptive" level, businesses implement adaptive, "self-optimizing" technology and processes. Among others, these include **intelligent control systems** that help equipment and machinery adapt in real time to changing inputs or environmental conditions, unlike more static and rigid control systems. This third level represents disruptive technologies that have the power to change entire industries and create new markets.

Autonomous control systems accelerate your digital transformation

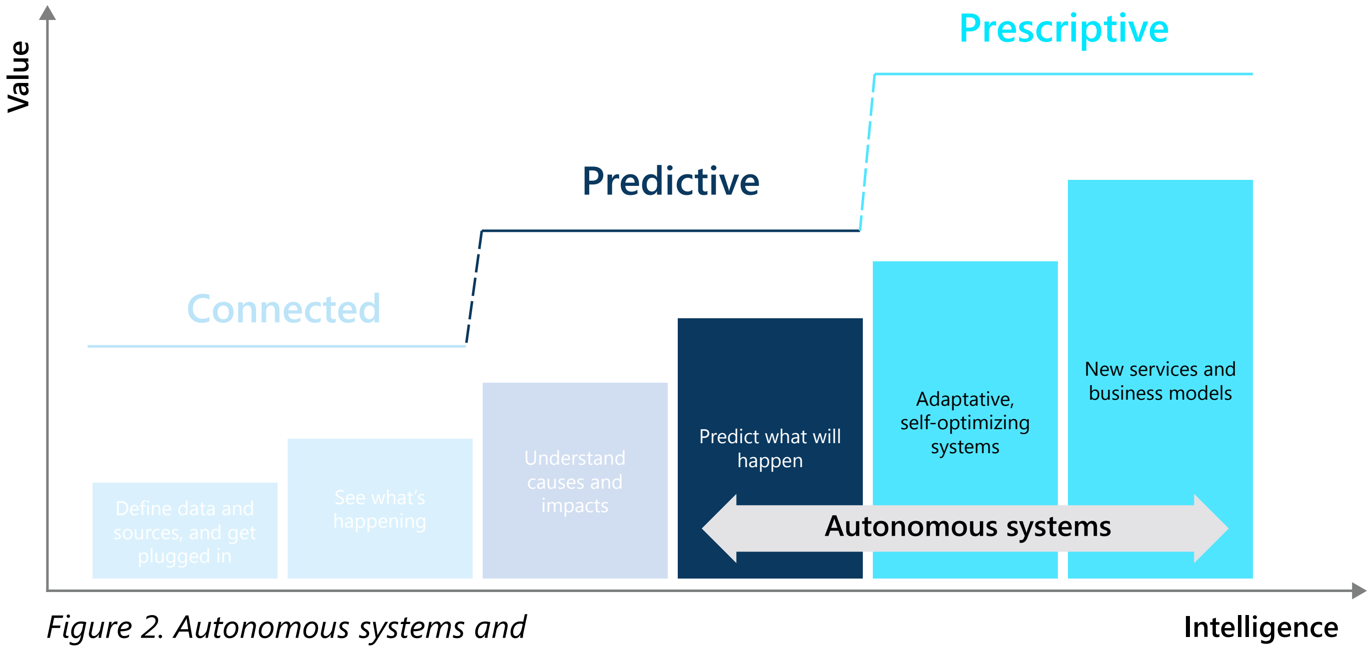


Figure 2. Autonomous systems and levels of intelligence in Industry 4.0.

The limitations of existing control systems

Industrial control systems form the backbone of businesses across sectors, but existing systems have limitations. Traditional controllers like MPCs, PIDs, and APCs operate on a set of deterministic instructions in predictable environments. While these control systems effectively perform one task at a time, human operators must manually retune machine settings for different scenarios, conditions, or goals. For example, an operator would have to adjust a bulldozer controller depending on whether it's operating in wet, rocky, or sandy soil. Additionally, these existing technologies are only capable of focusing on one optimization goal at a time–like maximizing throughput or minimizing energy usage.

There are user limitations to these systems as well. It's often difficult for operators and engineers to manage variables across disparate systems. Different levels of complexity within each system mean there are large gaps between what novice and expert operators can accomplish with them–making it difficult to ensure consistent management of systems across facilities. This is a challenge for many manufacturers–currently, 40% of manufacturers lack skills to build or run Industry 4.0 systems.[3] Achieving digital transformation means being able to take advantage of innovative technology and empowering employees to work more efficiently.

Limitations of existing systems:

- Inability to exercise control across changing scenarios and conditions
- Difficulty managing multiple or changing optimization goals
- Can't respond to unknown inputs
- Human operators perform inconsistently and take time to manually tune settings

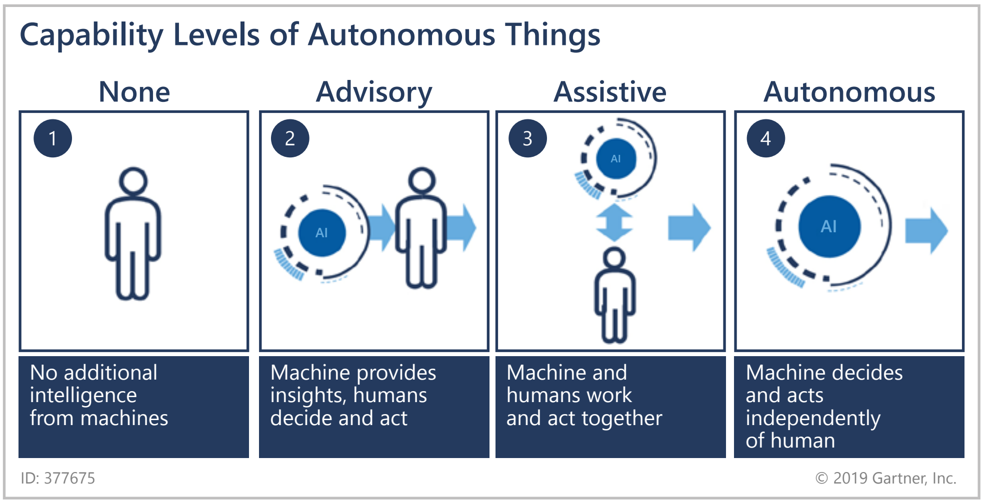
Autonomous control systems fuel innovation

Powered by artificial intelligence (AI), autonomous control systems go beyond basic automation. Instead of performing specific tasks repeatedly without variation, autonomous control systems adjust in real time to changing environments or inputs and even optimize towards multiple goals. For example, Schneider Electric uses an autonomous control system to have their HVAC systems simultaneously optimize for temperature comfort, CO_2 level compliance, and reduced energy consumption. And a food processing company created an autonomous extrusion line with extruders that adapt to variable inputs such as ingredient composition and moisture content.

As illustrated in the diagram *Capability Levels of Autonomous Things*, there are various levels of autonomy which can be leveraged in different scenarios. Simple "advisory" autonomy begins with systems predicting what's going to happen so employees can make informed decisions. More assistive technologies give employees suggestions and recommendations on the best course of action to take. In the most advanced capability level, machines and systems work completely autonomously, self-optimizing with limited human oversight and freeing up employees to focus on higher-value tasks. This doesn't mean that the entire factory or facility operates independently, but individual processes or machines might do so.

Autonomous control systems adjust in real time to changing environments or inputs and even optimize towards multiple goals

We've found that the most effective autonomous systems leverage a combination of digital feedback loops and real human experience. Digital feedback loops are the process of using real-time telemetry data to inform actions and recommendations, as well as historical data to drive operational or product improvements. Human involvement is valuable in two key ways. The first is that engineers and operators use their expertise to build the systems so they function well. The second is after deployment, there's



Source: Gartner, Top 10 Strategic Technology Trends for 2019: Autonomous Things (March 2019)

Example of Advisory	Example of Assistive	Example of Autonomous
Employees see machine status and make educated decisions as to when to schedule maintenance	Applications provide optimal timeframes for maintenance in order to avoid costly disruptions and minimize maintenance costs	Systems identify the ideal timeframes and schedule maintenance on their own

Figure 3. The typical evolution of autonomous things

always an opportunity to keep a "human in the loop" to oversee the solution and act on its recommendations.

These scenarios translate to significant business benefits. They unlock opportunities that weren't previously possible and drive significant improvements to throughput, efficiency, and quality. Autonomous systems can complete tasks like machine calibration and tuning faster than human operators and improve output quality by operating with higher accuracy and precision. They empower employees to work more efficiently, effectively, and at greater scale, enabling them to focus on the tasks that matter. No matter your use case, the potential business impact is substantial.

Introducing Microsoft Project Bonsai

At Microsoft, our vision is to empower industrial organizations to build and manage autonomous systems on their terms. These are complex systems that need to meet specialized requirements for every business. The majority of employees at manufacturing and energy companies are engineers, not data scientists, so these businesses often turn to third parties to build AI systems–leaving them with a "black box" solution that they can't easily troubleshoot or improve. Organizations should be able to create intelligent control systems using their unique subject matter expertise, without requiring advanced data science skills.

The Microsoft Project Bonsai platform makes this possible. Project Bonsai enables companies to innovate their most dynamic systems and processes with intelligent controllers. With our platform, subject matter experts are empowered to build and manage autonomous systems that are explainable, auditable, reusable, and trustworthy. And depending on their operational needs, companies can have controllers provide recommendations to operators or give them direct decision authority. This transformative innovation unlocks new possibilities and drives significant improvements in throughput, efficiency, and quality.

How Project Bonsai works

Subject matter experts in any industry can build the AI agent, or brain, that powers intelligent control systems through a unique combination of machine teaching, reinforcement learning, simulation, and deployment capabilities.

Identifying use cases where brains win

1. Highly complex systems
2. Competing optimization goals or strategies
3. Changing inputs
4. Unpredictable environments or conditions

Pioneered by Microsoft, **machine teaching** is a new, complementary approach to machine learning that can be used by those without AI expertise. With machine teaching, people break a complex problem into individual skills and give the AI brain important clues about how to learn faster. For example, in a warehouse and logistics scenario, an engineering team could use machine teaching to train autonomous forklifts. They would start with simpler skills like aligning with a pallet. Building on that, they could then teach the forklift to drive towards a pallet, pick it up, and set it down. Ultimately, the autonomous forklift would learn to detect other people and equipment and return to the charging station.

The platform uses the steps defined in the machine teaching process to inform the training process. The machine learning technique we use today is called **reinforcement learning (RL)**–in which AI learns by executing decisions and receiving rewards for actions that get it closer to an end goal. While traditional reinforcement learning is a time-consuming approach with lots of trial and error, machine teaching accelerates and improves the training process and even allows engineers to reuse the individual steps for other AI brains. Machine teaching also makes it easier to understand and audit the autonomous control system's behavior once it's been deployed, which is crucial for safety-critical applications.

Because companies can't afford to take critical equipment offline or risk damaging a system while the AI learns, the RL process takes place in safe and cost-effective **simulated environments**. For example, an AI brain learning how to control a bulldozer blade would receive information about the variables in the simulated environment, like the type of dirt or the proximity of people walking nearby, take an action, and then be rewarded accordingly. The AI brain improves its decisions over time to maximize its reward, and domain experts can tweak the reward system to arrive at a solution that works.

Traditional reinforcement learning

- Learns by trial and error
- Computationally inefficient

Combined with machine teaching

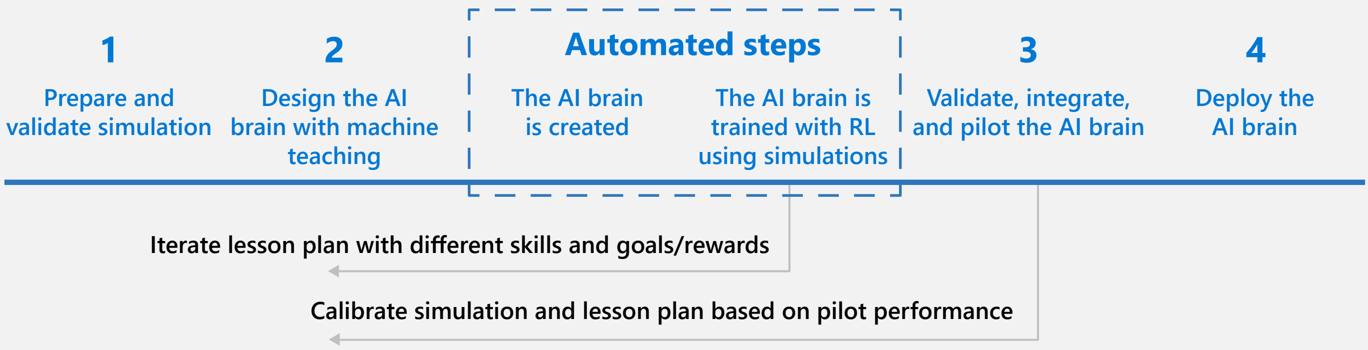
- Accelerates training
- Reusable steps and processes
- Explainable and auditable

Simulated environments can replicate millions of different real-world scenarios that a system might encounter, including edge situations like a sensor failure, so the AI brain can learn how to adapt. Companies can also train their AI brain quickly by running these simulations in parallel on Microsoft Azure. We work with an ecosystem of partners to ensure our platform is compatible with specialized simulation products like AspenTech and MATLAB, so engineers can reuse simulation designs they've already created.

Companies can **deploy** the AI brains in one of three ways: first, in the cloud, as a service that the controller computer can inference when needed. Second, on a device, integrated directly into an interoperable controller computer. And third, on the edge, using a companion computer that can communicate in real time with the controller computer.

Depending on their operational needs, companies can have the AI brain provide **decision support** for operators in some

AI brain training process



scenarios and give it direct **decision authority** in others. In a decision-support scenario, the solution integrates with existing IoT monitoring software to provide recommendations and predictions that drive consistency among operators and give less-experienced operators expert-level insight. And with direct decision-making authority, AI brains can develop creative solutions to situations that would challenge even the most experienced operators.

These capabilities are only the beginning of our autonomous systems journey. We'll continue integrating ground-breaking tools and services that help transform industrial sectors.

Microsoft Project Bonsai powers a wide range of use cases

From wind turbine optimization to machinery and robotics, Microsoft's Project Bonsai toolchain enables businesses to infuse intelligence into new and existing industrial control systems.

While any system can be enhanced with autonomous technology, we're focusing on three key scenarios for system optimization.

- Motion control: optimize movements and trajectory for things like robotic arms, bulldozer blades, forklifts, underground drilling equipment, and rescue vehicles.[4]
- Process control and automation: optimize throughput, efficiency, and quality for industrial processes—from consumer goods manufacturing and food processing to thermal reactors and evaporation control valves.
- Machine tuning and calibration: dramatically reduce machine downtime by calibrating machines faster and more precisely than what's possible with human intelligence alone.

Motion control case study: autonomous dozer blade control

Business problem

In order to prepare a dozer blade for a cut, operators need to tune a PID controller. This process can be repetitive and time-intensive, as tuning needs to happen for each new piece of equipment and cutting material.

Current method and limitations

Lifting and lowering dozer blades is a process controlled by five PID parameters. Operators may need to increase or decrease the parameters on-site if the default settings aren't suitable.

Objective and outcome of autonomous systems initiative

To improve this system, one company decided to train an AI brain to output control commands that adjust the dozer blade up and down in real time during a cut. This would maximize the waviness number, or flatness of the cut, on a single bulldozer at various speeds.

The AI brain was deployed to a special purpose CPU-based system connected to the bulldozer. Actions passed from the AI brain to the bulldozer in real time. As a result, the brain achieved a waviness number that exceeded the PID benchmark across multiple dozer models at multiple speeds.

Machine calibration case study: CNC machines at Siemens

Business problem

Like many other companies, Siemen's calibration of CNC machines was a manual, time-intensive process that required machine downtime and was often performed by third-party experts.

Current method and limitations

The machine calibration process requires expert human operators, takes an average of 20 – 25 iterative steps over more than two hours, and often lacks precision.

Objective and outcome of autonomous systems initiative

Leveraging mechanical engineer expertise, Siemen's built an AI brain to automate the calibration of machines in seconds or minutes instead of hours or days. They achieved two-micron precisions at an average of four to five iterative steps over 13 seconds. The system achieved incredible precision–less than one micron–in about 10 iterative steps and can calibrate multiple machine types and sizes.

Process control and optimization case study: wafer manufacturing process control

Business problem

Silicon epitaxy is grown in thermal reactors, which must be tightly controlled for uniform heating. Different phases of the process require different heat lamp settings to maintain optimal conditions in the reactor–these settings are also called a recipe.

Current method and limitations

The PID controller provides error correction in order to manage consistent temperature. The controller is only focused on heat distribution and doesn't consider other optimization goals like speed or energy usage.

Objective and outcome of autonomous systems initiative

This company built an AI brain to automatically control reactors–speeding up the process and saving costs. Ultimately, AI brain minimized the time and cost of growing wafer substrate above a target quality consistency.

Microsoft is democratizing the development of autonomous control systems using AI

With Microsoft's Project Bonsai solution, engineers can build smarter, more agile control systems that help their machinery and processes adapt in real time to changing conditions. Our solution enables engineers to apply their subject matter expertise to accelerate the development of these controllers and ensure they meet their unique requirements–all without needing a data scientist. Only with Microsoft can you deploy and manage intelligent control systems that are explainable, auditable, reusable, and trustworthy.

To learn more, visit the Project Bonsai website and contact the Project Bonsai team at bonsaiq@microsoft.com. Our Project Discover Worksheet and consultative sessions can help you determine how autonomous systems will best integrate with and power your business. See the solution in action with our Bonsai Hands on Lab.

[1] The Next Economic Growth Engine, World Economic Forum 2018
[2] Factory of the Future: Achieving Digital Excellence in Manufacturing Today, Microsoft 2019
[3] Forrester Infographic: Manufacturing Firms Look Beyond Core IT for Digital Capabilities, Forrester 2019
[4] Helping first responders achieve more with autonomous systems and AirSim, Microsoft 2019