Three Main Themes in the Industrial Internet of Things

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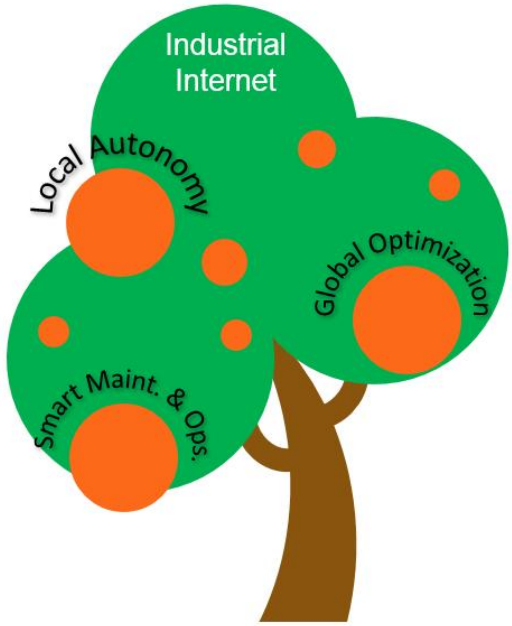
1. INTRODUCTION

The Industrial Internet is the application of the Internet of Things in industrial spaces, often referred to as the Industrial Internet of Things (IIoT). As IIoT develops, it is expected to fundamentally change the business landscape across the industrial sectors. The ability to create and execute an IIoT strategy becomes crucial to the continuing success of a business - increasing its value to customers, improving occupational condition, work safety and worker productivity, and enhancing its competitiveness in this shifting landscape.

Because the industrial sectors are broad and their operations diverse, the application of the Industrial Internet is consequently diverse and complex. Great variations exist in operational and regulatory requirements and in the maturity levels of various aspects (e.g. remote accessibility and the level of automation) of industrial systems. These variations give rise to many possibilities and options to apply the Industrial Internet concepts, practices and extensive capabilities to these systems to fulfill their promised values. When a business starts to formulate their strategy, devise its plan and chart its course to achieve the benefits that the Industrial Internet has to offer, the stakeholders must consider a myriad of factors and options to quantify the value of their IIoT investments and evaluate the best approaches to realize a return on their investment. Because the Industrial Internet is at a very early stage of development, many of these factors and options are yet to be well defined and present a high level of uncertainty. Moreover, we have few success stories to turn to as guide to assess if the investment will result in transformational outcomes.

Therefore, it would be helpful to ease these challenges by recognizing some common patterns in the application of the Industrial Internet across the industrial sectors. Despite diverse operations and applications across sectors, we do see emerging common patterns for Industrial Internet applications. In this article, we frame these patterns in three main themes to capture the essence of Industrial Internet applications: Smart Maintenance and Operations, Global Optimization and Local Autonomy.



Smart Maintenance and Operations focuses on optimizing maintenance and operations at the asset level. Global Optimization delivers system-wide operational efficiency by holistically analyzing operational data across fleets of assets to meet business objectives. Local Autonomy further achieves operational efficiency by enabling assets to adapt intelligently to changing operational context while increasing resilience in operations.

As the application of the industrial internet develops in these and other themes, we expect that new possibilities and opportunities will emerge enabling new classes of applications, creating new values and driving development of new technologies in a virtue cycle of advances.

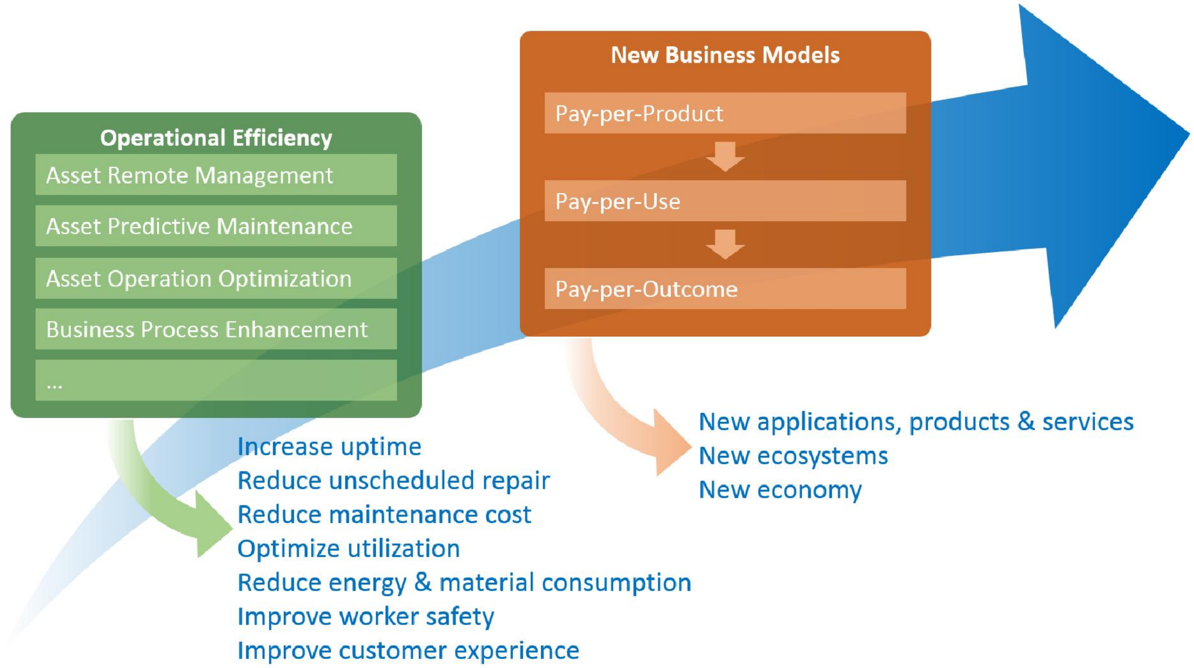
2. SMART MAINTENANCE AND OPERATIONS

Broadly speaking, industries at large have made hefty investments in the past decades building up a vast scale of infrastructure for industrial operations (the brown field). This infrastructure consists of a variety of assets, many of which operate at various levels of automation supported by micro-controllers connected to sensors and actuators performing closed-loop control. Today a large proportion of these assets still operate in isolation, some geographically distributed. The first phase of many Industrial Internet deployments will likely seek to connect to these assets to remotely monitor and maintain their operations. By doing so, we can gain timely visibility to the operational states of the assets and an ability to manage them remotely to improve uptime and reduce maintenance costs. This new monitoring capability allows us to remotely inspect the asset operations on demand and to be alerted to anomalies and exceptions in the operations. The new maintenance capability enables us to provision, configure, update, diagnose and repair the assets remotely. Moreover, data from the operational state of the assets can be analyzed to enable advanced capabilities such as predictive and prognostic maintenance to prevent unplanned downtime and further reduce maintenance costs through optimal field service planning (for service technician dispatch, spare parts management and client service scheduling).

Furthermore, after working hard to keep the assets up and running, we want to know how well they run and how efficiently they operate. By applying analytics on asset level data, we gain operational intelligence from various perspectives, including the asset conditions, utilization, output, process quality, and energy and material consumption in production. Based on such operational intelligence, we identify and address any gaps to ensure each of the assets produces the desired results efficiently.

These are among the much talked about benefits of Smart Maintenance and Operations and are recognized as the low-hanging fruit that may provide immediate ROI from the first phase of Industrial Internet deployments: improving operational outcomes and efficiency, and increasing customer satisfaction. There are many real world examples of this theme, some already existing and evolving (e.g. predictive maintenance on aircraft engines, rooftop HVAC systems, water supply systems and commercial coffee making machines) and many others are being considered and developed.

As we become mature in maintaining and operating the assets, we will gradually gain a higher level of competence and confidence in ensuring the reliable delivery of the desired outcomes. With this heightened level of competence and confidence, we may be able to obtain additional cost savings, e.g. by reducing the level of redundancy in the deployment of the assets and by extending the asset service or replacement cycles at least in some cases. Furthermore, we can enhance customer experience by offering stronger service level agreements (SLA), transitioning from a service model of product warranty to that of performance warranty. This will pave the way to transform the business model from product delivery to service delivery and from service delivery to outcome delivery. By progressing in this direction, we will witness the emergence of new applications, the rise of new ecosystems and finally the birth of a new economy.



We need to undertake a few essential tasks to enable Smart Maintenance and Operations. First, we need to retrofit the existing assets or build new ones to enable connectivity, data collection and remote management capabilities. Second, we need to establish asset management applications that perform aggregate maintenance on a large number of assets. Furthermore, we need to deploy streaming analytics and visualization capabilities to gain timely visibility to the asset operations. The analytics will become more advanced, progressing from describing the current operational states and conditions of the assets (providing visibility), to predicting how they would likely evolve (providing prognostics) and ultimately to prescribing the actions necessary for ensuring the desired operational outcomes (providing solutions). Finally, we need to integrate these applications with the business systems, e.g. resource and logistics management, work scheduling, customer relationship management and other domain-specific business systems, to streamline business processes that are involved.

We also face a few important challenges. The first challenge is how to implement rigorous security to thwart potential attacks against the enlarged attack surfaces of the assets now exposed by the connectivity and additional system elements in the network. The second challenge is how to add the new capabilities in a way without compromising the performance and safety of existing operations. The third challenge is how to create an ecosystem in which data sharing is incentivized so that different vendors of the assets are motivated to share data, enabling a holistic view and maintenance of the complete system.

The Industrial Internet Reference Architecture (IIRA) provides a reasonable framework for considering many of these concerns. It also describes some functional and implementation models as a starting point to conceptualize a system architecture for this theme. Furthermore, a team of security experts from the Security Working Group in the Industrial Internet Consortium (IIC) is delivering a security framework to address the security challenges. Another team within the Technology Working Group is starting to examine the challenges we are facing in the convergence of Information Technology (IT) and Operational Technology (OT), largely driven by the development of Industrial Internet. The challenges in building Industrial Internet ecosystems to realize the full potential and benefits of the Industrial Internet are also being raised and have generated much interest in the IIC.

3. GLOBAL OPTIMIZATION

With connected assets, we can go beyond the theme of Smart Maintenance and Operations that focuses on optimal operations per asset – to seek a higher operational efficiency at the system level; in other words, across fleets of assets. In seeking efficiency globally, we may require a coordinated increase in the level of operations at some assets and reduction at others based upon business objectives. An optimal global conditional plan might be developed to orchestrate the operations of the assets. The development of such a plan is based on the analysis of the combined operational intelligence and business insights and objectives, taking into account such factors as the availability of resources, the costs of the operation and the demands of the output. The global plan would then be dispatched to the individual assets to scale their operations up or down dynamically, with updates at increasingly shorter time intervals as technology improves. We see this Global Optimization of asset operations as the second theme of the Industrial Internet. We describe below a couple of examples to illustrate this theme.

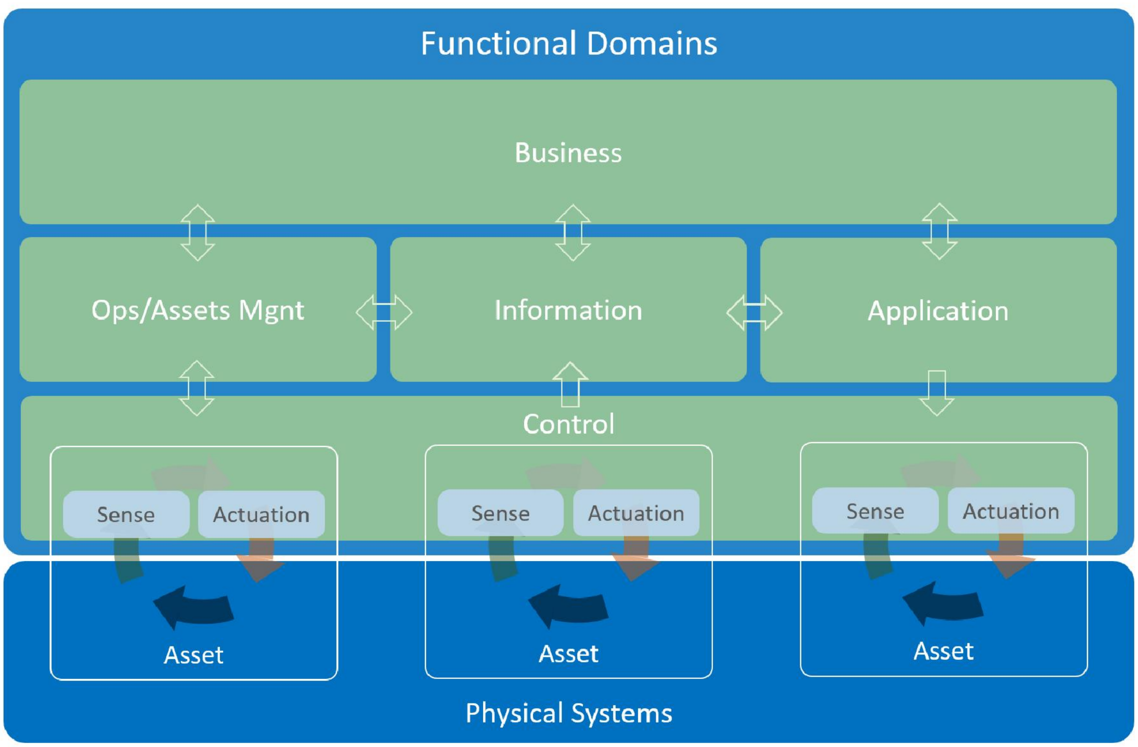
The first example is concerned with electricity generation. Today, an increasing proportion of generation is based on renewable resources that are typically unsteady and uncertain in supply. To meet this and other new challenges, a power plant operator (a Utility) might build an Industrial Internet system to automatically optimize (Economic Dispatch) the electricity generation levels among the set of generation assets under the operator ownership to meet the demand more efficiently. With the new system, a global generation plan within the Utility is optimized dynamically at regular time intervals[1]. The optimization takes into account such factors as demand (the total committed generation levels based on historical data and current situation), asset operation condition, energy source (e.g. wind, solar, tide, etc.) availability and its forecast, cost and price for each generation asset type and location. The generation level for each asset, based on the global plan, is then dispatched to each asset to effect the changes.

The second example involves low cost smart tags with attached sensors (e.g. for measuring temperature and humidity; detecting vibration and shocks). By attaching these tags to objects, we can track the movement of the objects, their condition and environment, from parts to

[1] It is understood that certain types of generation assets may take a longer time and higher cost to startup and shutdown and thus may be able to change states less frequently.

products, from factories to shipping facilities and to customers. There are considerable benefits just considering the logistics management of the movement of these objects alone. It could help to optimize the delivery of parts or products by assuring delivery quality (not damaged or spoiled), on-time delivery (optimal routes in response to changing conditions), security (preventing theft), safety (continuing monitoring to prevent hazardous condition and enabling fast response in case of accidents) and lower cost and impacts (optimized means of shipping). Many of these benefits can only be fully obtained with a real-time view of the assets (the smart-tagged objects as cargos; the trucks, trains, ships, plans and drones as transport assets) and the ability to globally optimize their movements.

The tasks required to realize the benefits from Global Optimization are complex and challenging. First, we need to identify existing inefficiencies in operations and key performance indicators measuring the efficiency and goals for improvement. Second, and more technically, we need to be able to measure the key performance indicators in real-time, apply algorithms and rules to determine the best course of actions for optimization and carry out the actions in orchestrating the operations of the assets – all dynamically. Another task is to integrate these operational processes with business ones, allowing the optimization to be driven by business objectives and constrained by rules of business governance.



The IIRA can be readily applied to support the Global Optimization theme. For example, the IIRA decomposes an Industrial Internet system into multiple functional domains. The Control Domain concerns the functions performed by the industrial assets. The Operations Management Domain deals with the functions for maintaining the assets to keep them up and running reliably – the focus of Smart Maintenance and Operations discussed in the previous section. The Information Domain provides functions for gathering data from the assets (as well as other domains), and transforming them into insights through analytics. The Application Domain focuses on the functions for orchestrating the operations of the assets to achieve optimal performance and high efficiency, globally, based on the analytic results from the Information Domain – the focus of the Global Optimization theme. Finally, the Business Domain consists of business functions to provide business objectives and constraints for optimization and to offer business support such as resource, logistics, work scheduling and customer relationship management for the smart operation of assets. The IIRA highlights the importance of integrating operational and business functions in order to achieve the full benefits of the Industrial Internet.

4. LOCAL AUTONOMY

As we work to realize the benefits of Smart Maintenance and Operations, and Global Optimization, it is tempting to build systems with a centralized architecture – one in which data from assets are collected and analyzed in a centralized system, likely in a public or private cloud, where operational decisions are made based upon the results of the analytics. This approach is likely a basic model for many initial IIoT deployments because of the overall simplicity of design and the efficiency offered by a large sharable pool of generic computational resources. This model would work well for use cases in which the operations of the assets involve few and infrequent decision-making from the centralized system. On the other hand, a centralized architecture may not work well in other cases. There could be technical constraints such as the latency involved in the decision-making loop and an undesirable dependency of the asset operations on the quality and availability of the network. There could also be economical constraints such as the cost of uploading a large volume of data over wireless networks.

One less obvious concern in a centralized architecture is the ever-increasing complexity of the system. The problems we seek to solve in the Industrial Internet are complex problems that are only getting more complex. As we drive toward a higher level of global optimization, more systems are connected together and the resulting complexity in the system of systems only grows. The relationship and dependence among the systems increasingly become untenably entangled. As such, centralized decision-making in such an environment would turn out to be ever more challenging. Any solutions we design would risk getting less stable. It might bring about too many bottlenecks, hotspots, weak-links and worse – even single-points of failure – in the overall system thus making it harder to achieve the level of resilience that is critical to industrial operations.

To address the issue of growing complexity in the overall system, it is advisable to distribute the complexity and decision-making across the system. This calls for solving the problems closest to its sources and in the context most conducive to the solution. This also calls for distributing decision-making to the entities where it is most appropriate and effective (e.g. situational awareness is most achievable). This finally calls for autonomy in the assets and the collaboration among them in proximity. This is the theme of collaborative Local Autonomy. In this regard, we have much to learn from the apparent global intelligence and resilience that emerges from swarm-like collaboration in schools of fish, flocks of birds, colonies of ants or bees in which the autonomous constituents execute only simple rules with peers in proximity.

Along this line of thought, as we pursue the next level of effectiveness and efficiency in operations, we may want to reexamine our current automated systems. There may be opportunities to extend the level of flexibility and adaptability of these systems to deal with conditions unforeseen when the automation systems were created. Additionally, many systems, though largely automated, still involve a human-in-the-loop in the operation workflow. The need for a human-in-the-loop could be due to situations in which cognitive capability may be required to solve specific, complex problems. As we become more apt in applying cognitive capabilities in these systems, we may want to reduce the reliance on humans in operations to increase reliability, efficiency and safety. Think about the examples ranging from robotic aids to human workers in warehouses, underground autonomous mining machines and the well-publicized autonomous vehicles. In these autonomous systems, we elevate the human role from the operational level to the mission control level – setting objectives and handling exceptions. These systems would have an increasingly higher level of capability to learn and adapt – capable of extrapolating parameters possibly outside the range of the original test set, trying out solutions according to its risk evaluation and confidence level. In the process, they would learn and expand the range of the test set for safe operations, autonomously.

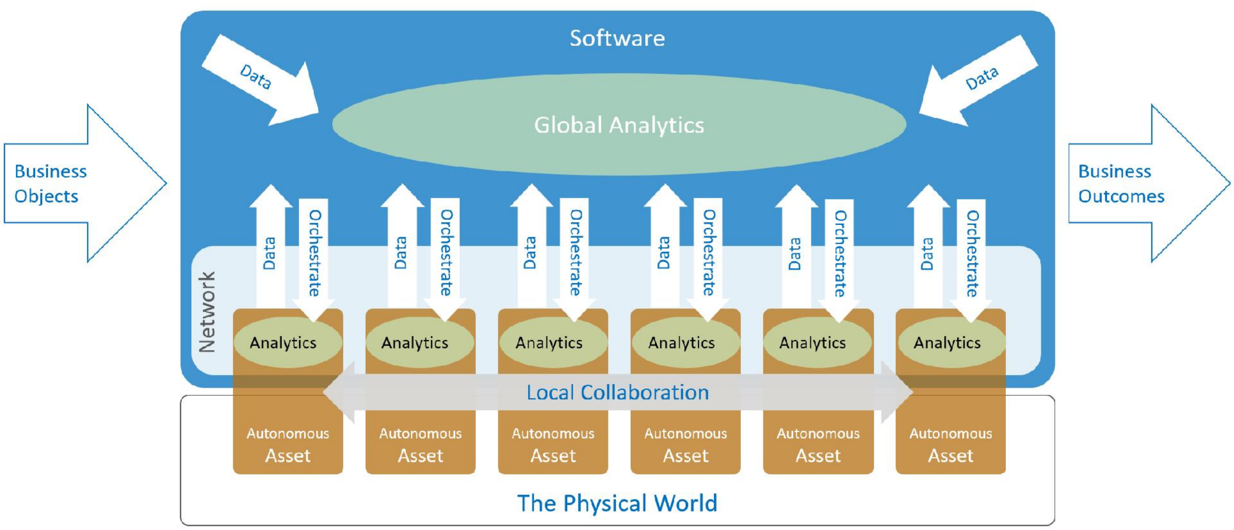
As the level of autonomy grows at the asset level, we will improve resilience, security and safety of operations in the overall system. Each asset no longer always depends on the global network or system to continue its operations and at the same time becomes more capable to deal with and recover from localized adversary conditions making the operations more resilient. With more decision-making shifted to them, the intelligent assets now have a stronger ability to assess the validity of requests from the centralized system or from its peers so to accept only those compatible with its a priori objectives, making the operation more secure and safer.

To build collaborative systems with distributed autonomy, in other words, to achieve distributed problem solving and decision-making, we need appropriate system architectures with the right world modeling, analytics and computation platforms, well-distributed and well-interconnected computation capabilities, many of them, closest to the physical assets.

Fortunately, the continuing advances in computation and communication that have ushered us into the era of the Internet of Things are also enabling us to achieve distributed and collaborative autonomous problem solving. The greater embeddable computational capabilities, increasingly packaged in miniaturizing sizes, consuming less energy and available at lower cost, are enabling the execution– closer to the assets – of more advanced analytics and better modeling of the world. This will help to transition the assets from automation to autonomy. At the same time, the ubiquitous connectivity among the assets and from them to the broader systems is making it possible for the autonomous assets to collaborate with each other seamlessly within proximity and to be coordinated across the network by entities with a purview of a larger scope – the idea of Global Optimization.

With such progresses, we can foresee that the patterns of distributed problem solving will become more dynamic in response to the changes in the nature and complexity of the problems as they develop. The systems will extend the capability to dynamically distribute computation for analytics and problem solving close to where the problems are – in a way similar to the Big Data architectural principle of moving the computation to where the data are, however, in a much larger scale with much greater complexity. In these systems, newly developed and verified algorithms, models and approaches for problem solving are shared with and adapted by the individual autonomous assets[2].

As we push forward in this direction, we can recognize the emerging role that software plays at every level of a system, in both enabling autonomy in the assets as well as collaboration among themselves and coordination by broader systems. In the near future, we can envision a world in which the physical world including the industrial assets is bound together by the fabric of software. The physical world will be constantly sensed and optimally operated by software, driven by advanced analytics at various levels – creating a 'Software-Defined World.'



A key task of achieving collaborative autonomy in the overall system is to recognize the pattern of complexity of the problem, on which the scheme of distributing the complexity across the system is based. Another task is to determine the nature and level of autonomy to be embedded in the assets or other sub-systems, and the types and levels of collaboration needed among them. This is followed by the task of identifying the algorithms, models, analytics and frameworks required to support the autonomous decision-making at the asset level in additional to the types of sensing required to gather the necessary data for the computation.

[2] As oppose to through configuration as in the centralized paradigm prevalent in today's systems.

As we are at the very first stage of this revolution, the biggest challenge we face is that the lack of experience in how to build collaborative autonomous systems that are not only functional in operation but are also secure, safe and resilient. We expect a hastening pace in advanced research and development in both technologies and frameworks in comprehensive physical modeling, Machine Learning, Cogitative Computing and Artificial Intelligence to meet this great challenge. Technology advances in autonomous vehicles and other robotic systems have taken great strides in this direction and what we learn in these areas will be of great value as we move forward in other industrial areas.

Another key challenge is the long lifecycle of the industrial assets that last for decades during which the cyber (computational) portion of the assets would likely evolve several generations while its physical counterpart may remain relatively stable. Therefore, as we build new smart assets (cyber-physical systems - CPS) or retrofit existing brown-field assets, we need to strive to design CPSs with cyber components (computational hardware and software) not only seamlessly integrated with their physical counterparts but at the same time 'pluggable,' allowing them to be upgraded over time at a pace different from that of their physical counterparts.

The idea of distributing complexity and problem solving (involving decision-making) is one of the many topics getting strong interest and attention within the IIC Technology Working Group. For example, the topic of distributed analytics is under active discussion by the Industrial Analytics Task Group. The topic of how to advance from integrability, to interoperability and finally to composability is being explored. Dynamic Composition and Automated Interoperability, a chapter in the recently published IIRA, outlines the concept of an agent-based design allowing clear abstraction of models, capabilities and controls from the details of implementation and infrastructure complexity, and then providing real-time binding between them. These topics will be developed further within the IIC to address some of the challenges we are facing in this area.

5. SUMMARY

To conclude this article, we outline Smart Maintenance and Operations, Global Optimization and Local Autonomy as the three main themes in Industrial Internet system implementations. Although with different focuses and emphases, all these themes aim to realize greater values through achieving operational efficiency while enhancing safety and resilience. A given IIoT deployment may emphasize some of these themes or some combination of them; it may even evolve through them in a different order. As with any attempt to abstract systems with great complexity and diversity, the analysis of these themes inevitably over-simplifies some aspects or omits some others in specific systems. Nevertheless, they may still be useful as a starting reference to evaluate specific IIoT deployments, to understand its values and objectives and to anticipate its potential challenges. To have a clear understanding of these values is of foremost importance since after all, it is the business values in IIoT systems that drive their development.

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