Digital Twins and Automated Manufacturing Systems: A Comprehensive Survey of Emerging Industry 4.0 Technologies

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***Abstract*—The current landscape of Industry 4.0 within the last two years(2021 - present) is an ever-changing landscape of possibility and emerging technology. For this industrial manufacturing and automation survey, we aim to provide a subjective overview of a few critical advancements within this field. This survey's focus encompasses various emerging and conceptual robotics and digital twin technology applications in automation. Modern articles, journals, and YouTube videos provide a lens into the world that has evolved over the last two years. Industrial automation is seeing applications in robotic metal manufacturing and an unexpected application in radiation treatments with a proposed nanorobotic delivery system. Digital twin technology is being used increasingly to provide optimal models for HVAC systems in power plants, intelligent factory security, and testing the viability of electric vehicles. Overall, it is abundantly clear that the push for many of these research projects is due to the need to optimize old processes supporting the march toward green technologies. Of the technologies discussed, the most viable ones to become more accessible in the next decade are incremental metal forming, DT technology for electric car prototyping, virtual power plant DTs for HVAC system evaluation, and performance on an electrical grid, and the holistic smart factory security DT(SMS-DT).**

***Index Terms*—Artificial Intelligence, Robotics, Digital Twins, Industry 4.0, Automation, Incremental Sheet Forming, Robo-Forming, Nanorobotics, Factory Security.**

I. Introduction/Background

Industry 4.0 is a heavily debated topic in today's society. Many argue that we are on the cusp of this fourth industrial revolution, while others advocate that we all live in this era. Regardless of these opinions, one thing is sure: new and emerging technological advancements are being revealed quickly. This survey aims to investigate novel technologies emerging within the last five years (2018 - 2023) and examine what strides are being made. Industry 4.0 has many branches and disciplines within its overarching scope. We will then evaluate the viability of each of these technologies and make predictions as to which will be the most promoted advancements in the coming decade(by 2033).

A. *What is Industry 4.0*

Industry 4.0 refers to the fourth industrial revolution, which integrates digital technologies into various aspects of manufacturing and industry. This concept builds upon the previous three industrial revolutions, which were marked by significant advancements in manufacturing processes:

1) First Industrial Revolution (late 18th to early 19th century): Characterized by the mechanization of production through water and steam power.
2) Second Industrial Revolution (late 19th to early 20th century): This was marked by the advent of electricity and the assembly line, leading to mass production.
3) Third Industrial Revolution (mid-20th century): The rise of electronics, automation, and computerization in manufacturing.

Industry 4.0 introduces a new wave of technological advancements, including:

1) Internet of Things (IoT): Connecting devices, machines, and systems to collect and exchange data.

2) Artificial Intelligence (AI): Using intelligent algorithms to analyze data, make decisions, and optimize processes.
3) Cloud Computing: Storing and accessing data and applications over the internet, facilitating collaboration and scalability.
4) Additive Manufacturing (3D Printing): Building objects layer by layer based on digital models.
5) Big Data Analytics: Processing and analyzing large volumes of data to derive insights and inform decision-making.
6) Digital Twin Technologies: Virtual representations of devices, a network of devices, or industry settings used for data gathering, analysis, machine learning, and AI prototyping. DT's endeavor to accurately model all system components, including physics, for a 1:1 representation of their real-world counterparts.

The goal of Industry 4.0 is to create "smart factories" where machines, systems, and people communicate and respond to critical events in real-time. This interconnected and data-driven approach aims to improve manufacturing processes' efficiency, flexibility, and productivity. It also enables the customization of products, predictive maintenance, and a more agile response to market demands.

B. What is a Digital Twin?

Digital twins are a virtual representation of a physical device or object that models and emulates its behavior and statistical data. For example, a digital twin of an old car odometer would be designed to closely model the physics of the numbers turning on the dial based on the revolution of its gear system. It would also report the torque on these systems and model the numbers revolving as expected from this type of device. This example is pretty simplistic regarding what a digital twin can achieve compared to a more sophisticated application, such as modeling the Mars rover.

II. Industry 4.0 Emerging/Novel Technologies

A. Nano Robotics in The Radiation Field

As part of a conceptual design, Hyo Sung Cho and Tae Ho Woo are developing a means to change the traditional methods of the radiation treatment industry. By using nanorobotics, they proposed a tadpole-like design that will contain an isotope to deliver radioactive treatments directly to affected areas for cancer patients. By utilizing this method, they believe a 1cm cancerous mass could be treated 5nm at a time as the robot can swim in circles around the afflicted area[01a]. What's interesting about this conceptual design is the precision of how the robot delivers the correct dosage of radiation to the targeted area. Automation of this process is very complex, given the nature of the human body. Still, it will be a beneficial advancement for the radiation industry.

B. Incremental Sheet Forming(Robo-Forming)

In Los Angeles, Machina Labs has created a new way to create formed metal using industrial robots. The robots implemented in their operation are from companies such as KUKA and FANUC. However, Machina Labs does not use proprietary software from each manufacturer; instead, they have designed their methods to produce formed metal more safely and efficiently. For context, traditional metal-forming is achieved by two laborers working on a sheet metal press brake. The brake head and hydraulic cylinders pressure the metal to intentionally deform it from a flat surface, creating tight angles or other radius-style bends. This process begins with an end product, such as water tanks or metal trays.

Unsurprisingly, the traditional methods of sheet forming are not without their risks. "Statistically, 83 percent of the reported sic(metal forming) injuries occur in areas of the press brake that are not protected by existing safety product designs[Dig23]." These are known as pinch points and have led to dismemberment, crushing injuries, or even death in some cases. Due to these hazards, Machine Lab's robots use a very different process in which the metal sheet is suspended in a fixture like a portrait. The material is then sculpted a plane at a time. Two robots are used for the process, one applying pressure by pushing into the metal and the other supporting and slightly pinching the surface edge.

Deforming the metal utilizes a method similar to a potter's wheel for sculpting clay. However, for this approach, the robot's EOT(End Of Tooling) effectors spin on the newly formed edges in tandem while maintaining constant force(both pushing and pulling) via feedback from the joints and positional data[Sma23]. While this forming may not be fast for some products, it alleviates the need for traditional laborers to put themselves at risk when creating similar products.

III. Emerging/Novel Digital Twin Utilization in Industry 4.0

Another aspect of Industry 4.0 is digital twin technologies' implementation and conceptual designs. With digital twins, complex devices can be modeled, more data can be gathered, statistical analysis can be conducted, and machine learning or AI applications can be applied. These new applications are used to bolster the next generation of models for existing devices, rapid prototyping for novel technologies, or monitoring and security purposes. These devices are also being developed to test and model mission-critical hard real-time systems. The following sections are a survey of the conceptual creation of a digital twin and examples of recent implementations of these virtual tools.

A. AI Digital Twins: Holistic Factory Security

Utilizing a three-layer SMS-DT architecture, the GECAD-Research group in Porto, Portugal, aims to improve safety and security for the manufacturing shop floor. As stated by the researchers, "The SMS-DT is an integrated platform to simulate and monitor industrial conditions in a digital twin-based architecture.[Mai+22]." With this DT model, the group can monitor equipment states, sensors, human interactions between robots and terminals, robot-to-robot communications, and many other data points. They store these values in a data lake, which is also responsible for tracking human facial images and their interactions at their stations with their mouse and keyboard setups. "The digital twin module mirrors the cognitive status of the employees, energy, and network state[Mai+22]."

The DT network setup utilizes Eclipse Ditto(an open-source digital twin application). It allows the group to store information based on specific "things" or equipment. The feedback from the sensors and equipment is relayed through HTTP or MQTT protocols, and then the data is made available via the REST API. All data for "things" are encapsulated as JSON objects for versatility and flexibility in accessing URLs. For the human element of this monitoring, the facial image system for employees and equipment interaction metrics are used to promote safety. While this may seem like a big brother move for a DT to be somewhat invasive in this manner, safety is at the core of its implementation. The SMS-DT can determine if they are stressed or tired by monitoring employees' posture and responsiveness to their tasks. This feedback for the company helps update production schedules for specific employees or discuss what tasks could be updated with an automated solution.

Analyzing these patterns and systems with AI or ML as part of the digital twin's implementation provides even more insight into not just a single factory floor. Still, it can be applied to industry trends within similar product manufacturers on a macro scale. With the safety evaluations included, the SMS-DT can provide valuable insight into the most dangerous and accident-prone product processing for companies to focus on enhancing.

B. AI Driven Digital Twins: Smart Manufacturing and Robotics

[01b]

C. Electric Car Design, Testing, and Performance Testing Using Digital Twins

The prospect of using digital twins in the automotive industry is an exciting venture. Imagine being able to emulate a vehicle's performance under any conditions you want to test and seeing the feedback from the car's systems in a virtual environment. The article "Review of Electric Vehicle Testing Procedures for Digital Twin Development: A Comprehensive Analysis" addresses that. The main questions this type of application aims to answer are what benefits a digital twin can provide electric car manufacturers and what drawbacks exist when implementing such models.

One advantage of a functioning digital twin is that the car manufacturer can simulate and analyze real-time data before the vehicle design enters the factory. Knowing if a new electric car model should hit the factory line or require more fine-tuning would be highly cost-effective. Automakers would be enticed to invest in the ability to test the car's battery life, onboard computer systems, and safety features. However, the difficulty lies with our current state of digital modeling technology. Expense is always a factor when developing a digital twin, and according to the article, ”Ensuring seamless integration of data from multiple sources, maintaining accuracy in virtual representations, managing computational requirements, and verifying DT predictions against real-world results are necessarily obstacles that need to be addressed.” [Rja+23] These are significant issues for digital twin technologies and many physics models for computers to achieve a one-to-one representation of reality.

D. Data Driven Modeling of Virtual Power Plants Using Digital Twins

The models proposed in this article pertain to modeling HVAC systems in VPPs(Virtual Power Plants) that are modeled using a digital twin implementation. Wind turbines, the electrical grid exchanges for the power plant, and the cooling systems are all modeled. The DT uses existing research from other power plants as part of its base ML data set. Two ML methods were applied: one that used an ANN and another that used LR methods to train each model.

In their findings, the researchers reported that ”The ANN-based HVAC model performed the best, and the LR-based model performed the worst. In short, a model similar to the actual HVAC system can be created based on past operation data through data-based modeling, even if the HVAC system’s physical characteristics and BIM are not known in detail[Par+23].” Based on this, they found that the VPP was viable to being closely related enough to the actual functionality of a realistic power plant based on a goodness of fit test. As part of their future work direction, the researchers would like to further optimize the VPP’s performance through the implemented digital twin technology for the project.

IV. Discussion

Based on the examples of Industry 4.0 technologies discussed, a few stand out as ones that will be advanced and still around in the next decade. Incremental metal forming, while still a niche type market, looks promising in becoming a big contender in the custom product new steel market. With improved robotics hardware in the next decade, production could be sped up and increased. There is also potential for Machina Labs to expand their factory operations to accommodate the demand for these types of complex geometries.

There is also a case for a ”smart” factory (SMS-DT) to accommodate more complex behaviors from external attackers on the factory floor, with quantum computing technology close to its initial release. This model was also subject to the restrictions of today’s hardware and other technologies, such as AI. In the next decade, with those criteria being improved, there is a decent possibility that the SMS-DT could be rolled out on a macro scale, and the team could achieve its goals to make critical good responses no matter the factory layout it is implemented in.

Electric car DTs will thrive if, within the next decade, at least one automaker decides to take a risk and invest in this technology. Certainty for this project is not guaranteed due to the politics involved with such an investment, which is estimated to be in the billions for research and development. A decade may also be a short time frame for what is needed to model all the systems in a computer. There is still a case regarding hardware advancements and those in machine learning and AI to help aid in developing and implementing this kind of DT, especially for rapid prototyping.

Lastly, while limited by AI research, the virtual power plant DT may be the one that reaps the most benefits in the next ten years. This team has a viable working ML model that exists as the basis for the DT, which is impressive and lessens the possibility of it not being used in future implementations. With AI development being the buzzword in 2023, it would come as no surprise that advancements in this field are and will keep coming out more rapidly. As it goes, future research for this project may ride the wave of development quickly and become released within a decade.

V. Conclusion

This survey establishes many interesting emerging technologies across the Industry 4.0 landscape. The most viable ones are incremental metal forming, electric car DTs, the holistic smart factory, and the VPP DT for HVAC systems. Nanorobotics, while conceptually and mathematically proven for some cases of operation, still have unknown cases that need to be solved. Within the next decade, will advancements and accessibility to quantum computing help further these projects? Will other computer engineering technologies emerge that will increase motor drive speeds and designs of factory robots? These questions and more are tough to answer now but not far off on the horizon of Industry 4.0. Perhaps by 2033, we will finally see society announce that the 4th industrial revolution is indeed underway and witness even further evolutions of the technologies discussed in this research survey.

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