Internet of things enabled manufacturing: a review

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Abstract: Internet of things (IoT) plays an important role in the manufacturing sector, allowing objects to be sensed and/or controlled remotely across existing network infrastructure, creating opportunities for more direct integration of the physical world into computer-based systems, and therefore resulting in improved efficiency, accuracy and economic benefit in addition to reduced human intervention. With the world-wide spread of Industry 4.0, IoT-enabled manufacturing is now one of the key supports to smart factory, intelligent automation, and real-time adaptive decision-makings. This paper comprehensively reviews related technologies and world-wide movements so that insights and lessons could be useful for academia and practitioners when contemplating IoT technologies for upgrading and transforming traditional manufacturing into an new future in the context of Industry 4.0.

Keywords: internet of things; IoT; cyber-physical systems; CPS; manufacturing; Industry 4.0; review.


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1 Introduction

Manufacturing, as one of the backbones for a country or district, is on the cusp of a revolution since advanced technologies are making typical manufacturing systems smarter and smarter. Smart factory, regarded as an essence of Industry 4.0, could be enabled by internet of things (IoT), cyber-physical systems (CPS), and cloud computing (Lee et al., 2015; Trappey et al., 2016). IoT-enabled manufacturing refers to an advanced principle where typical production resources are converted into smart manufacturing objects (SMOs) which are able to sense, interconnect, and interact with each other to intelligently carry out manufacturing logics (Zhong et al., 2013a). It plays a critical role in smart factory due to its ability to create modular structured components which are equipped with smart decision-making capability. In modern manufacturing, the potential for IoT to improve productivity and automation in the production process is vast. It was claimed that IoT has set in motion the idea of Industry 4.0 which is a new wave of changes decentralising production control and triggering a paradigm shift in manufacturing field (Bi et al., 2014). When manufacturing resources becoming more and more interlinked, IoT-enabled manufacturing can reduce work-in-progress (WIP) items, increase productivity, and improve product quality.

Most companies care about the physical flows which are created by the manufacturing activities so as to add values for various materials in specific production sites such as shop floors or assembly lines. By making full use of IoT technology, such flows are synchronised with their information flows which are created by different kinds of digital devices deployed in the production environment (Dai et al., 2012). Thus, physical SMOs will be inextricably linked to their information flows. For example, a piece of raw material \( X \) will tell us that “I am a key component for product \( Y \) which is ordered by customer \( Z \).” Within the IoT-enabled manufacturing environments, thousands of SMOs create a digital world where the manufacturing processes are streamlined and automated, the production decision-makings are optimised and adapted, as well as the operational activities are revolutionised and visualised (Tao et al., 2014a; Zhong et al., 2016a). Digitisation in manufacturing field based on IoT could ultimately be used to reshape time and labour-consuming operational tasks.

IoT has been kept in the eyes of industry practitioners and academia for decades. In order to comprehensively investigate the IoT-enabled manufacturing, this paper firstly attempt to review this topic by selecting 147 articles mainly from Scopus and Google Scholar databases. Key technologies used in IoT-enabled manufacturing, for example IoT, cyber-physical system (CPS), Wireless Manufacturing, and data analytics are covered in Section 2. World-wide movement in this area is reviewed in Section 3 which highlights several major districts such as Europe, North American, Asian Pacific, etc. Section 4 gives a review of the applications of IoT-enabled manufacturing. Section 5 concludes this paper by highlighting some key observations/insights and suggestions.
2 Key technologies

This section aims to provide comprehensive background knowledge and context on the topic of IoT-enabled manufacturing. This will be further broken down into IoT, CPS, wireless manufacturing, and data analytics which are the most practical and influential technologies used in IoT-enabled manufacturing.

2.1 Internet of things

The IoT can be seen as transforming ordinary physical objects into smart objects by embedding smart sensors and an identity/personality. Li et al. (2015) argued that the exact definition is still not agreed upon, but does agree that IoT can be treated as a superset of connecting devices uniquely identifiable. They also presented a commonly accepted definition of IoT: “a dynamic global network infrastructure with self-configuring capability based on standard and interoperable communication protocols where physical and virtual ‘things’ have identities, physical attributes, and virtual personalities and use intelligent interfaces, and are seamlessly integrated into the information network” (Xu et al., 2014). A few other definitions can be seen in Haller et al. (2008) and Uckelmann et al. (2011).

Table 1 Implementation approaches

<table>
<thead>
<tr>
<th>Models</th>
<th>Key characteristics</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 layer models</td>
<td>Perception layer</td>
<td>Yun and Yuxin (2010), Jia et al. (2012) and Domingo (2012)</td>
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<tr>
<td></td>
<td>Network layer</td>
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<td></td>
<td>Application layer</td>
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<tr>
<td>4 layer models</td>
<td>Sensing layer</td>
<td>Xu et al. (2014) and Zhang et al. (2015)</td>
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<td>Network layer</td>
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<td></td>
<td>Service layer</td>
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<tr>
<td></td>
<td>Interface layer</td>
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<tr>
<td></td>
<td>Resource layer</td>
<td>Tao et al. (2014b)</td>
</tr>
<tr>
<td></td>
<td>Perception layer</td>
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<tr>
<td></td>
<td>Network layer</td>
<td></td>
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<tr>
<td></td>
<td>Service layer</td>
<td></td>
</tr>
<tr>
<td>5 layer models</td>
<td>Edge technology layer</td>
<td>Bandyopadhyay and Sen (2011)</td>
</tr>
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<td></td>
<td>Access gateway layer</td>
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<td>Internet layer</td>
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<td></td>
<td>Middleware layer</td>
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<td></td>
<td>Application layer</td>
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</table>
Figure 1  Statistics analysis on RFID research (a) documents by year (b) documents by subject area (c) documents by type (d) documents by country/territory (e) documents per year by top five sources (see online version for colours)
Regarding the architecture of the IoT, it is widely accepted that a service oriented architecture (SOA) is best (Karnouskos et al., 2009; Spiess et al., 2009; Zhang et al., 2017b). The key benefits that SOA offer are how dynamic and adaptive it is, allowing reconfigurability and interoperability (Cannata et al., 2008; Guinard et al., 2010). Additionally, it can treat a complex system as a set of well-defined simple objects or subsystems, allowing for reusability yet still maintaining individuality. This decoupling allows software and hardware components to be reused or upgraded separately which are similar to those of encapsulation and decoupling in object oriented programming. There are many approaches to the implementation and structure of this architecture, each with varying numbers of layers which are listed in Table 1.
Al-Fuqaha et al. (2015) also offered a look at many different architectures for IoT. The core of each of the models is similar: each contains a stage that utilises smart objects and sensors to enable data generation about the state and environment of that object. Another stage is to communicate the data between objects and to apply the knowledge behind the data. There exist many benefits of connecting manufacturing resources and machinery in the IoT-enabled environment such as communication between resources and machines in and of itself allows for smoother automation, and a greater degree of tracking and control from a logistics point of view. This ubiquitous connection of smart objects also enables the use of other paradigms, such as: predictive manufacturing (Gao et al., 2015), cloud manufacturing (CMfg) (Tao et al., 2011, 2014a; Liu et al., 2011; Xu, 2012) and big data analytics (Bin et al., 2010; Chen et al., 2015; Zhong et al., 2016b). These paradigms bring manufacturing into a new era which is Industry 4.0 where physical processes could be monitored, a virtual world could be created, and decentralised decisions could be made (Lee et al., 2015; Zhong and Huang, 2014; Liu and Xu, 2017).

IoT is enabled by a few key technologies which have had extensive progressive in the last few years. The two main technologies are: radio frequency identification (RFID) and wireless sensor networks (WSNs). RFID allows for unique, fast, and easy identification and tracking of objects without the need for line of sight. It consists of two parts: the tag and the reader. The tag is essentially a microchip attached to an antenna with a housing, and stores a unique electronic product code (EPC), typically storing 64–96 bits, as per EPCglobal standards (Atzori et al., 2010). Tags can be split into two categories: passive and active RFID tags, referring to the power supply.

The RFID readers trigger the tags transmission by generating a signal to which the tags respond. Typically, passive RFID tags are the most commonly used in industry (Zhong et al., 2013b). RFID tags can be split into their operating frequency, low frequency (LF), high frequency (HF), and ultra-high frequency (UHF) (Dobkin and Wandinger, 2005). Despite the benefits offered by RFID, such as low cost and small size, it also has constraints, for example, it cannot provide detailed information about objects state, pin-point position, or environment. It more or less provides unique identification and general positional area (Lu et al., 2016, 2017). It also has no processing power, so it cannot perform logic or filter/clean any data (Wang et al., 2014).

RFID research has been attracted particular attention in recent years (Ahmad and Mohan, 2014; Dimakopoulou et al., 2014; Leung et al., 2014; Zhong and Huang, 2014; Zhong et al., 2014, 2015a, 2015b, 2016c; Mejjaoui and Babiceanu, 2015; Tesch et al., 2015; Lu et al., 2016; Saab and Msheik, 2016). From Figure 1(a), it could be observed that, from the year of 2008 to 2016, the total documents published are 23,713 with the average of 2,635 documents per year. The major subject areas are shown in Figure 1(b) from where engineering and computer science take up 39% and 36% respectively. From Figure 1(c), most of the documents are from conference papers and articles. RFID books are fewer (only 84) compared with other types such as notes and review. As shown in Figure 1(d), the most active research countries/territories are China, US, South Korea, Taiwan, and Germany where RFID research in terms of technologies and its applications are popular. Figure 1(e) presents the top five sources about the keyword ‘RFID’. They are IEEE Antennas and Propagation Society APS International Symposium Digest, Advanced Materials Research, Applied Mechanics and Materials, Communications in Computer and Information Science, and Lecture Notes in Computer Science Including Subseries
2.2 Cyber-physical systems

CPS refers to a mechanism or principle which uses computer software and physical components to build a deeply intertwined system so that internet and its users could be seamlessly integrated. While, this term has been widely extended, thus, there are many definitions, some of which can be found in Table 2.

<table>
<thead>
<tr>
<th>Definition descriptions</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>The integration of computation with physical processes. Embedded computers and networks</td>
<td>Lee (2008)</td>
</tr>
<tr>
<td>monitor and control the physical processes, usually with feedback loops where physical</td>
<td></td>
</tr>
<tr>
<td>processes affect computations and vice versa.</td>
<td></td>
</tr>
<tr>
<td>Systems that feature a tight integration between computation, communication, and control</td>
<td>Wang (2010)</td>
</tr>
<tr>
<td>in their operation and interactions with the task environment in which they are deployed.</td>
<td></td>
</tr>
<tr>
<td>A cyber physical system integrates computing, communication and storage capabilities</td>
<td>Sanislav and Miclea</td>
</tr>
<tr>
<td>with monitoring and/or control of entities in the physical world, and must do so</td>
<td>(2012)</td>
</tr>
<tr>
<td>dependably, safely, securely, efficiently, and real-time.</td>
<td></td>
</tr>
<tr>
<td>Cyber-physical systems are a next generation network connected collection of loosely</td>
<td>Tan et al. (2008)</td>
</tr>
<tr>
<td>coupled distributed cyber systems and physical systems monitored/controlled by user</td>
<td></td>
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<tr>
<td>defined semantic laws.</td>
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</table>

Another defining aspect of CPSs are their characteristics. There is much literature attempting to characterise CPS, each with slight differences. Some examples can be found in (Shi et al., 2011; Wang et al., 2015; Jazdi, 2014). Lee et al. (2015) summarised the characteristics as two main functional components:

1. The advanced connectivity that ensures real time data acquisition from the physical world and information feedback from the cyber space.
2. Intelligent data management, analytics, and computational capability that constructs the cyber space.

Despite the abundant definitions and characteristics, it can be hard to visualise. In the context of manufacturing, CPS can be the mirroring, networking, and controlling of physical systems via cyber space (Wang et al., 2015). Each physical machine would have a cyber-twin that mimics the real physical machine, holding all information about the current and previous state of that physical machine, such as action, temperature, vibration, etc. (Xu, 2017). These cyber-twins would be able to communicate via a network, which could be the internet, but not necessarily. Additionally, the cyber-twin
can control the physical machine, with feedback loops to ensure the convergence of states between the physical machine and cyber-twin (Lee et al., 2013, 2015).

The benefits of CPS are obvious from the literature. The interconnectedness of devices enables a greater degree of automation and tracking, but this connectedness and data generation can be exploited for further benefits (Zhong et al., 2015b). Key benefits can be summarised into three key categories: enhancing decision making, information sharing, and enabling other manufacturing concepts. Enhancing decision making can be seen as the utilisation and visualisation of big data analytics, aiding human decision making, or enabling cyber decision making. Human decision can be aided through increased transparency via visualisation of big data (Kretschmer et al., 2017). Transparency can be defined as “the ability of an organization to unravel and quantify uncertainties to determine an objective estimation of its manufacturing capability and readiness” (Lee and Lapira, 2013). By knowing the manufacturing floors capability and capacity, management can make better decisions (Zhong et al., 2014; Wang et al., 2016). Cyber decision-making can be seen as any resolutions made by the cyber hub as a result of analysing the sensor data (Petrya and Austin, 2016). These can include prognostics and health management (PHM), predictive manufacturing, and resource flow and logistics optimisation (Lee et al., 2014b; Chen et al., 2017). PHM aims to analyse current and historic states of a machine to predict when maintenance is needed and useful remaining life. By avoiding unnecessary maintenance, costs can be reduced and uptime increased. Lee et al. (2015) outlined how to design a CPS for the purpose of PHM in resource flow and logistics optimisation aiming to optimise resource routes and the manufacturing process overall. The goal of predictive manufacturing is to determine what a user wants and start manufacturing it before an order is placed, or even know what they want (Lee et al., 2014a). This will reduce turnover time and increase satisfaction.

Enabling other manufacturing concepts includes some advanced concepts such as CMfg and Industry 4.0 which may use CPS for future applications or industry revolution. By enabling the widespread adoption of these concepts, quality of the product will be increased since there will be less defects. CPS will generally increase efficiency of the manufacturing industry in terms of both inputs, such as resource, energy, and man hours, as well as outputs, such as the final product or service (Almada-Lobo, 2016).

2.3 Wireless manufacturing

Wireless manufacturing can be thought of as “an umbrella term for manufacturing solutions enabled by wireless devices such as RFID and other types of wireless devices” (Huang et al., 2009). In manufacturing environment, companies are looking hard for innovative approaches to leverage wireless manufacturing principles to enable more efficient operations so as to increase the customer satisfaction. Today, manufacturers are using great myriad of wireless equipment and applications such as automated production robots, unmanned logistics vehicles, and so on (Wu and Zhou, 2007; Fantoni et al., 2014; Lu et al., 2016). That brings significant benefits such as speeding the products and services delivery, increasing the manufacturing efficiency and effectiveness, as well as improving the product quality and manufacturing systems’ reliability (Zhong et al., 2016b).
Table 3  Typical applications of wireless manufacturing

<table>
<thead>
<tr>
<th>References</th>
<th>Industry company</th>
<th>Aims</th>
<th>Wireless</th>
<th>Future work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virkkala (2007)</td>
<td>Agricultural industry, Finland</td>
<td>• Exam the innovation processes driven by wireless networks</td>
<td>Nokia networks</td>
<td>• Adopt more advanced ICT for the SMEs</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>• Nokia Siemens networks application</td>
</tr>
<tr>
<td>Dai et al. (2010)</td>
<td>Discrete industry, China</td>
<td>• Design and develop a hardware platform for a paperless manufacturing</td>
<td>RFID and 433 MHz</td>
<td>• Advanced base station for better communication</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• More easy-to-deploy/configure system</td>
</tr>
<tr>
<td>Peng (2008)</td>
<td>CNC system, China</td>
<td>• Design a wireless communication for CNC system</td>
<td>2.4 G Bluetooth, ISM frequency channel</td>
<td>• Machining and manufacturing information integration</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>• NC machine tools control</td>
</tr>
<tr>
<td>Makris et al. (2012)</td>
<td>Robotic assembly, Greece</td>
<td>• Enable the RFID-based robotic assembly operations</td>
<td>RFID and ethernet</td>
<td>• A networking framework for communicating with robot controllers</td>
</tr>
<tr>
<td>Rajesh et al. (2010)</td>
<td>Industrial application, India</td>
<td>• Propose an architecture to integrate the sensor network and internet using cloud technology</td>
<td>Temperature sensor network, cloud</td>
<td>• Distributed manufacturing with sensor network</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Intelligence integration into the internet</td>
</tr>
<tr>
<td>Abdullah et al. (2015)</td>
<td>Production line management, Malaysia</td>
<td>• Design an RFID-enabled production line management system</td>
<td>RFID and ZigBee</td>
<td>• Hardware configuration</td>
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<td></td>
<td></td>
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<td>• Software program improvement</td>
</tr>
<tr>
<td>Barenji et al. (2014)</td>
<td>FMS, Turkey</td>
<td>• Deploy an RFID-enabled distributed control system</td>
<td>RFID and sensor network</td>
<td>• Distributed control systems structure</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Improve definitions of WSN and DCS</td>
</tr>
<tr>
<td>Dubey et al. (2017)</td>
<td>Framework implementation, India and US</td>
<td>• Develop a conceptual framework for wireless manufacturing implementation</td>
<td>RFID, Wi-Fi, 3G/4G</td>
<td>• More impact factors on the implementation</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>• Technology integration analysis</td>
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</table>
Under the era of Industry 4.0, smart sensors for manufacturing systems are essential so that remote management and control using wireless devices must be implemented in front-line production sites like shop floors. There are surrounded obstructions, interference, and obstacles in such areas. For example, RFID signals will be confined in a metal surrounded environment when using HF (Wang et al., 2012). Therefore, hybrid wireless solutions are needed to improve the communication reliability under complex situations. More reliable, consistent and intelligent wireless standards are adopted to wireless manufacturing so that they can automatically adapt to dynamics and interference (Huang et al., 2008). For instance, a smart Gateway in a plug and play fashion was introduced following service-oriented architecture so as to manage various manufacturing objects in assembly workstations (Zhang et al., 2011). Taking full advantages of the multi-agents technology, the smart gateway is able to define, configure and execute manufacturing operations on a real-time basis via wireless standards (Zhang et al., 2014).

There are large number of applications using wireless manufacturing concepts. Table 3 lists several typical applications by highlighting the industry/company, aims, wireless standards, and future work.

From Table 3, it could be observed that wireless manufacturing has been widely applied in different industries and fields where different wireless technologies have been employed. In the early stage, wireless standards like 433 MHz are mostly used in industrial applications due to its frequencies used in most nations worldwide. Recently, Bluetooth and Wi-Fi are more focused in the industrial implementation as the maturity of the emerging wireless technologies and the deceasing of their prices. Some cutting-edge wireless fashions like 5G was introduced in some conceptual frameworks in industry for example Germany whose manufacturing systems are the leading applications in the world.

### 2.4 Data analytics

Data analytics plays a very important role in supporting IoT-enabled manufacturing where decision-makings are based on various data. It refers to the processes of examining large number of datasets by using specific systems or tools so as to excavate useful information and knowledge (Zikopoulos and Eaton, 2011; Zhong et al., 2017a). Typically, vast data will be generated within an IoT-enabled environment such as a shop floor. Such data carry rich information and knowledge which is hidden and implicit so
that knowing the value creation is significant for the manufacturing companies to boost their business. Data analytics was introduced to properly identify the value creation processes by using parallel-processed approach (Furtado et al., 2017). Take RFID in the production line for example, work flow process systems could be enhanced by using the captured data after data analytics to increase the total throughput (Curran et al., 2013). With the promising advantages when using data analytics for improving their business, large number of companies adopt this technology in their enterprise and shop floor decision-making levels, especially in the context of Industry 4.0 era (Jeschke et al., 2017; Lu, 2017; Zhong et al., 2017b, 2017d, 2017c).

Table 4 Top IoT companies for manufacturing industry

<table>
<thead>
<tr>
<th>Featured</th>
<th>Company</th>
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<tr>
<td>IoT startups</td>
<td>Samsara</td>
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<td>Notion</td>
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<td>Hologram IoT</td>
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<td>Losant</td>
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<td>Bastille</td>
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<td>Helium</td>
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<td>Filament</td>
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<td>Konux</td>
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<td>Hardware</td>
<td>GainSpan</td>
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<td>Samsung ARTIK</td>
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<td>Particle</td>
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<td>Libelium</td>
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<td>Link Labs</td>
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<td>Qualcomm IoT</td>
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<td>Silicon</td>
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<td>Lantronix</td>
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<td>Software</td>
<td>ProSyst</td>
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<td>Litbit</td>
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<td>Antmicro LTD</td>
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<td>DGLogik, Inc.</td>
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<td>Cloud vendors</td>
<td>Ayla networks</td>
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<td>Xively</td>
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<td>PTC</td>
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<td>Arrayent</td>
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<td></td>
<td>Buddy</td>
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<td></td>
<td>SensorSuite Inc.</td>
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<td>System</td>
<td>AMYX+</td>
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<td>integrators</td>
<td>TreeLine Interactive</td>
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<td></td>
<td>ThingLogix</td>
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<td>Flex</td>
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Some specific techniques and tools are used in various manufacturing fields to capture, process, and analyse data. For example, in an industry IoT application, a hybrid reader transceiver was proposed to integrate asymmetric UHF/UWB so as to achieve high throughput transmission (Mao et al., 2016). Using the captured real-time data, product life-cycle energy management system could be realised (Tao et al., 2016). The energy consumption data from design, production, and service are analysed using statistics tools. In order to process the data from CPS-based systems, a node-link diagram visualisation technique was proposed (Gürdür et al., 2016). Additionally, a data-driven performance prediction approach was introduced to evaluate the design alternatives (Zhang et al., 2017a). A rough number-based decision-making trial and evaluation laboratory (DEMATEL) method is discussed and a case study is given to demonstrate the feasibility of the proposed approach.

Data analytics is also widely used in different applications. Liu et al. (2016) introduced a pilot project in China which is using the internet of agricultural things for tracking and tracing the supply processes through data analytics. Civerchia et al. (2017) reported a data analytic application for advanced predictive maintenance in industrial IoT monitoring. In modern product emergence processes, it is important to use the data analytics for making decision under cloud environment. Thus, Wallis et al. (2014) talked about an intelligent utilisation case of using digital manufacturing data for decision-making. Liu and Zhong (2017) presented a set of applications in manufacturing field where data analytics is used in terms of successful cases and practical implementations. Branger and Pang (2015) discussed some possible integrated services like data analytics for the networked manufacturing in the era of Industry 4.0.

2.5 Comparison

As mentioned previously, there are many similarities between CPS and IoT which utilise ubiquitous sensing and computing, transforming ordinary objects into smart objects, with the vision of enabling communication between smart objects and a central hub. The key difference is that CPS does not necessarily need to be connected to the internet, the network it operates on can be a closed local network. This implies that CPS is broader in concept, and IoT is a CPS specifically connected to the internet (Wang et al., 2015; Jazdi, 2014). However, due to the lack of a unified definition of CPS, it is argued that CPS belongs to the broader term of IoT (Wan et al., 2013). Other minor differences are that CPS specifically emphasises the feedback from the cyber to the physical, i.e., the actuation and control, where IoT does not. Additionally, it seems that from literature, IoT incorporates the use of RFID much more compared to CPS, and both heavily employ the use of WSNs. Despite the semantics, they all aim to increase connectivity between objects and devices and to make them smarter. By doing so it allows the use of advanced manufacturing strategies and technologies with the ultimate goal of Industry 4.0.

Large number of companies from different perspectives such as software and hardware are providing different technical support to enable the IoT solutions for manufacturing sector. Table 4 summarises some top IoT companies which are able to support the IoT manufacturing from various categorises. Table 4 presents the companies with their major expertise.
3 World-wide movement

It should be noted that although IoT is a subcategory of CPS, IoT is a more widely used term within the public. Thus many sources refer to only IoT, however this does not discredit the relationship between IoT and CPS, and any insights gained regarding IoT movements can also be applied to CPS.

3.1 Europe

The GDP of the European Union is estimated to be $16.3 trillion USD as of 2015, with approximately 24.4% of that attributed to industry. In this case, industry is defined as the value added through manufacturing, mining, construction, electricity, water, and gas (Innovalia Association, 2016). It is also estimated that 15.7% of the GDP is contributed by manufacturing alone. This means there is a large potential market for IoT/CPS enabled manufacturing, approximately a $2.6 trillion USD market.

Many sources attempt to estimate the benefits IoT can bring to the EU’s GDP. A.T. Kearney, a management consulting firm, estimated a 7% increase in GDP by 2025, with $160 billion Euros contributed by the manufacturing industry (Collignon et al., 2016). A joint report by Fraunhofer Institute and Bitkom estimated that German GDP can be increased by a cumulative of $267 billion Euros by 2025 through the introduction and utilisation of Industrie 4.0 (Heng, 2014). In this case, cumulative refers to the benefits of each year, accumulated. It is difficult to judge the accuracy of these estimates, but it is clear that these sources agree that IoT and CPS strategies can bring about significant increases in Europe’s GDP, which can be viewed as an opportunity now to invest.

Figure 2 EU-funded projects since 2000 (see online version for colours)

All EU funded projects are made public within the Community Research and Development Information Service (CORDIS) portal (CORDIS, 2016). Within this, a search was made with the following search term: (‘Internet of Things’ OR
‘Cyber-Physical Systems’ OR ‘IoT’ OR ‘CPS’ OR ‘Wireless Manufacturing’) AND (contenttype="project"). This searches for specifically projects that includes any of the key words mentioned. The results were then sorted by year and shown in Figure 2.

It is clear that there is an increasing number of projects over time, which is an indicator that the area is still growing. There are several European initiatives that try to enable IoT and CPS, notably Horizon 2020 (H2020), which is part of the greater Europe 2020 strategy. H2020 is the largest EU research and innovation program to date, with $80 billion Euros of funding from 2014 to 2020 (European Commission, 2015). Within the scope of H2020 exists many initiatives relating to IoT. For example, an initiative specific to manufacturing is the ICT Innovation for Manufacturing SMEs (I4Ms) (SmartAnythingEverywhere, 2015). The goal of this initiative is to “ensure that any industry in Europe, big or small, wherever situated, and in any sector, can fully benefit from the digital innovations to upgrade its products, improve its processes and adapt its business models to the digital change” (Innovalia Association, 2016). Another initiative relating to the overall implementation of IoT is the digital single market (DSM), under the Europe 2020 strategy. This was adopted in 2015, including 16 initiatives. The main goals of DSM are to improve consumer and business access to digital goods and services, create the right environment for digital networks and innovative services to flourish, and maximises the growth potential of the digital economy, all of which can culminate to $415 billion Euros in additional growth (Digital Single Market, 2015). Despite being a general IoT initiative, it does however contribute to the R&D of IoT manufacturing. This clearly shows the governments belief in the benefits of CPS and IoT in manufacturing, and suggests it would be easy to gain government backing regarding related decisions.

As for current utilisation, in 2011 it was reported that 3% of EU companies are using RFID. Of those companies, 56% use it for access control, 29% for supply chain, 25% for motorway tolls, 24% for security control, 21% for product control, and 15% for asset management (Van Kranenburg et al., 2011). Note that the sum is over 100% because some companies can be included in more than one category, for example a company may use RFID for both access control and supply chain management. Although this is not representative of manufacturing companies, it is clear that there is a lack of adoption of this technology with companies.

3.2 North American

As of 2015, North America’s GDP is estimated at $19.6 trillion USD, with 20.6% of that contributed by industry, and 12.3% from manufacturing alone. This means a $2.4 trillion manufacturing market. The International Data Corporation (IDC) has predicted that by 2020, there will be 7.5 billion connected devices, compared to the 3.1 billion estimated for 2013. They have also predicted an IoT revenue of $1,922.1 billion USD in 2020, compared to the estimated $667.9 billion USD in 2013 (Lund et al., 2014). A graph of the growth can be found in Figure 3.

Although there are differences in numbers between this and other sources, such as MicroMarketMonitor (2016) and Grand View Research (2016), the general trend is the same, a compounded annual growth of between 16% and 23% for the years up till 2020. Thus, there is a general consensus in the market revenue growth of IoT in North America. Within the US, the majority of research and initiative funding is allocated by the National Science Foundation. Since the year 2000, they have been increasing the money allocated...
to the topics of CPS and IoT. Figure 4 depicts the number of projects that has received funds over the years, and the total amount award to those projects up to date.

**Figure 3** Growth of IoT devices connected in North America (see online version for colours)

![Predicted Revenue from IoT and Connected Devices in North America](image)

**Figure 4** Awards in North American since 2000 (see online version for colours)

![Number of Awards and Total Dollar Amount Awarded per year](image)

An upward trend can be seen in both the amount of projects award funding and the amount of funding. However, it can also be seen that in the year of 2016, there is a
decrease in the number of projects and the dollar amount funded to those projects. There are several possible explanations. First is related to the database of the NSF website. The data shown in the graph was retrieved near the end of 2016, however it may not have updated the database with some 2016 projects, leading to a lower number and dollar amount of projects and awards. The second is related to research itself. As a concept becomes a ‘hot topic’, the easier avenues of research are conducted first. Eventually it will lead to only leaving the more challenge issues, to which many researches may not want to participate in.

In a recent PwC report of 120 US manufacturing professionals, it was found that “thirty-five percent of manufacturers are currently collecting and using data by smart sensors to enhance manufacturing/operating processes; 17% plan to do so in the next three years, with another 24% with plans, but no timeline” (PwC, 2015). Of the surveyed 120 companies, 34% believe it is extremely critical to adopt IoT strategies, whilst 60% believe it’s moderately or slightly crucial. Despite the small sample size and possible skewedness, a resounding majority believe IoT strategies are at least slightly crucial.

3.3 Asian Pacific

In 2013, the GDP of the combined East Asia and Pacific region was $21 trillion USD, whilst industry made up 34.7%. Manufacturing made up 23.1% of the GDP alone, translating to a $4.9 trillion USD manufacturing market. Revenue generated in the IoT market in the Asia Pacific region in 2015 was observed to be approximately $439.6 billion USD, and is expected to grow to $853.9 billion USD by 2020 (Statista, 2016c). This suggests that the IoT market in this region will double in five years.

In China, a strategic plan called Made in China 2025 was proposed with the Guidance of the State Council on Promoting Internet + Action and 13th Five-year Plan on national Program for Science and Technology Innovation. Made in China 2025 has clear goals, guidance and road map for 30 years. There are nine missions and ten major development fields and give major programs (Li et al., 2017). In 2009 China has identified CPS as one of its major interest in the next stage of economic growth (Wang, 2010). Beijing plans to invest five billion yuan ($800 million) in the IoT industry by 2015. The Ministry of Information and Technology estimates China’s IoT market will hit 500 billion yuan ($80.3 billion) by 2015, then double to one trillion yuan ($166 billion) by 2020. (http://www.edition.cnn.com/2012/11/28/business/china-internet-of-things/).

Recently, Japanese government initialised an Industry 4.0 plan which aims to create standards for technology to connect factories and to combine efforts to internationalise industrial standards from Japan. Mitsubishi, Fujitsu and Panasonic, some of the initiative’s founding members, plan and act global this initiative to make a difference. Nissan Motor is also a member, which looks for areas of collaboration instead of understanding this as a competing model to Industry 4.0. ‘Intelligence Japan (I-Japan) strategy 2015’ was also launched in 2009, to promote convenience of life and stimulate new vitality in this area (Zhang and Zhu, 2011).

3.4 Overall movements

By comparing the movements of the countries in the world, it can bring forward insights into which regions currently lead the IoT and CPS markets, and which regions
Figure 5 is a graph of the number of published papers found on SCOPUS sorted into the top 15 countries. The searching term used was: 
“(TITLE-ABS-KEY("Internet of Things") OR “Cyber-Physical Systems”) AND (“Manufacturing”)”. This specifically searches all papers title, abstract, and keywords for the terms ‘manufacturing’ and either ‘internet of things’ or ‘CPS’ or both.

It can be seen that the Asia Pacific region clearly leads in the number of publications, with the European Union behind, and North America last. This is not too surprising, considering the Asia Pacific region has the largest manufacturing market ($4.9 trillion USD as of 2013), with Europe also coming in second ($2.6 trillion USD as of 2015), leaving North America last ($2.4 trillion USD as of 2015). This means the Asia Pacific region has the most to gain from developments in IoT.

Many sources have attempted to estimate the future of IoT. Gartner predicts that in 2020 there will be 26 billion units, compared to the 0.9 billion units recorded in 2009, due to the low cost of adding IoT capabilities to consumer devices (Rivera and Van der Meulen, 2013). Cisco has predicted that by 2020 there will be 50 billion connected devices on the internet (Evans, 2011). Statista also predicts 50 billion connected devices by 2020, with an observed 14.4 billion devices in 2014 (Statista, 2016a). The 50 billion estimate however has been retracted by the original author, and placed around 30 billion, which is more in line with the current estimates (Nordrum, 2016). Therefore it is commonly agreed that there will be approximately 20 to 30 billion connected devices by 2020, a massive number of connected devices when compared to the human population.

Another way to gain insight into the future of IoT markets is to look at the sensor market (Perera et al., 2014). According to BCC Research’s 2014 market report, the estimated compounded annual growth rate between 2015 and 2020 for the sensor market is 10.1% per year, growing from a $95.3 billion market to an estimated $154.5 billion.
Additionally, the RFID market is expected to grow from $12.6 billion in 2016 to $24.5 billion in 2020 (Statista, 2016b). The growth in both these markets can be indicative of the coming growth in IoT and CPS applications, as they require sensors as a perception layer.

We can also compare the expected benefits and adoption rates of IoT. A 2015 report by Tata Consultancy Services suggests that adoption of IoT is biggest in North America and Europe. Of the surveyed companies, North American companies spend an average of 0.45% of revenue on IoT initiatives, whilst European companies spend 0.40% of revenue. Asia-Pacific companies spend 0.34%. Manufacturing companies also reported the highest revenue increase of 27% when compared to other global industry sectors in the year of 2014. In 2014, it was observed that manufacturing companies spend an average of 0.57% of revenue on IoT initiatives, an average of $121 million US (Tata Consultancy Services Limited, 2015).

In a separate survey of 465 business professionals in late 2015, it was estimated that 29% were using IoT at the time, with an additional 14% planning for implementation within 12 months, and another 21% planning implementation after that (Gartner Inc., 2016). This means 64% currently use or eventually plan to implement IoT strategies. It should also be noted that 28% do not plan to implement IoT and 9% see no relevance in it whatsoever. However there are two major hurdles identified, the first being business related and the second being organisation related. Businesses do not yet know the full benefits IoT can yield and have not yet invested the time to determine what IoT can bring to their business. The organisational problem is lack of IoT expertise within the staff. Since it is a reasonably new concept, it is not surprising that many companies do not have people with expertise in that area.

3.5 Discussions

It should be clear that IoT and CPS strategies are widely expected to grow, in terms of the number of connected devices and market size. It is also reasonable to extend this to IoT and CPS strategies within a manufacturing context, in fact it may even be led by manufacturing, as hinted in (Tata Consultancy Services Limited, 2015), with the industrial manufacturing sector as the second highest spending per revenue, and with the highest revenue impact. The natural extension of this growth is the widespread adoption within industry. Companies that fail to adopt this paradigm will most likely fail in the future, as they will slowly be outperformed due to the relatively large marginal increases in efficiency IoT and CPS can bring. This is similar to what happened to Motorola. This growth can also induce a positive feedback loop. As more companies incorporate IoT technologies as part of operations, more data is generated and shared. Algorithms may extract and confirm more hidden information from the larger dataset, yielding more benefits, thus looking more attractive and causing more people to want to adopt IoT strategies.

From the review of technology and world-wide movements, several insights and lessons are obtained so that industrial practitioners and academia could be guided when they are contemplating IoT-enabled manufacturing application and research. Firstly, IoT key technologies like RFID, Bar-code, and wireless communication standards are quite mature in industry applications. However, their integrations such as technical and data integration are scarcely reported. That may result in isolated technology implementation in entire manufacturing sites. For example, parts being produced communicate with
machines by means of a product code, which tells the machines their production requirements and which steps need to be taken next and all processes are optimised for IT control, resulting in a minimal failure rate.

Secondly, successful cases are scarcely reported since most of the implementation of IoT-enabled manufacturing is still in the initiative stage. Best practices and case studies require more implementations of IoT technology in the industry so that manufacturing could be better transformed and upgraded.

Thirdly, the IoT-enabled manufacturing is still led by developed countries like US and Germany. For example, most of the top IoT technology providers are from these countries. Few of them are from developing countries like China and India. Developing countries like China are chasing rapidly due to the government plans or programs. In the near future, these countries may be the biggest market for IoT technology and their applications.

Manufacturing worldwide is on the cusp of a revolution where new information technologies are suddenly offering not only to make the management of manufacturing more effective from early versions of plant and enterprise software, but the work itself smarter. Technologies based on the IoT have the potential to radically improve visibility in manufacturing to the point where each unit of production can be ‘seen’ at each step in the production process. Batch-level visibility is being replaced by unit-level visibility. This is the dawn of IoT-enabled manufacturing. IoT-enabled manufacturing requires a healthy dose of technology to ensure machines work together, material flows visibly in real time, and teams of knowledge workers orchestrate the entire manufacturing process. The IoT-based environment enables this possibility, for example in plant floor applications, it can create a network linking a range of manufacturing assets from production equipment to parts being produced, from sensor-embedded automation controls to energy metres, from trucks to a warehouse’s smart shelves (Zhong et al., 2017a).

With the IoT, manufacturers can give each of their physical assets a digital identity that enables them to know the exact location and condition of those assets in real time ubiquitously throughout the manufacturing sites or even the whole supply chain. Very importantly, IoT-enabled manufacturing also requires proactive and autonomic analytics capabilities, making manufacturing an intelligent and self-healing environment. With IoT-enabled manufacturing, companies can predictively meet business needs through intelligent and automated actions driven by previously inaccessible insights from the real world. It transforms manufacturing businesses into proactive, autonomic organisations that predict and fix potentially disruptive issues, evolve operations and delight customers, all while increasing the bottom line.

4 Applications

Despite what seems to be a lack of adoption of intelligent strategies for manufacturing, there are still many large companies that have successfully utilised them to enhance efficiency. In terms of new technological adoption, it is generally the larger or newer companies that adopt first, because they either have the money to spare, or they can implement without retrofitting. Small and medium sized companies that are already established would have to either retrofit existing infrastructure, or replace them, maybe even both. This can be implied from (Tata Consultancy Services Limited, 2015),
indicated by the difference between median and mean amounts companies spend on IoT initiatives in 2015. The mean is $86 million USD, whilst median is $4.2 million USD. This big difference is due to outlier companies spending extremely large amounts on IoT initiatives, drastically changing the mean but not the median.

One such company is Siemens’ Electronics Manufacturing Plant, located in Amberg (Kreutzer, 2014; Hessman, 2013). This factory produces PLCs, achieving a 99.9985% quality of production through the use of intelligent manufacturing strategies. To put this into perspective, the factory produces approximately 12 million units per year, of this only 180 of them will be defective. Machines and computers handle 75% of the value chain via automation, each product dictating their own production process. As a product approaches a machine, its product code is communicated to the machine informing it of what requirements the product has or needs, and what needs to be done. This demonstrates the automation power intelligent strategies can bring to the shop floor. The extension of this would be automatic process optimisation, such as a generating a priority order of products based on upcoming deadlines. In addition to this, the factory can achieve 100% traceability as it generates around 50 million pieces of process information every day.

Siemens’ also has an Electronics Work plant in Chengdu, China. Although the intelligent strategies are not as deeply integrated as the Amberg plant, it still manages to save approximately $116,000 Euros through energy efficiency savings. Another company that has derived benefits from IoT is Rolls-Royce. They have over 13,000 commercial aircraft engines which they produce and maintain. IoT allows them to utilise predictive maintenance on these engines, which is aptly named their Engine Health Management (EHM) program (Rolls-Royce, 2016; Microsoft, 2016).

Each engine is fitted with about 25 sensors, providing information about its state and environment, with many for pressure and temperature, vibration, etc. This aggregated over every engine results in “terabytes of data coming from large aircraft fleets, with gigabytes per hour – rather than kilobytes – to process and analyze”, quoted by the Senior Vice President of Rolls-Royce, Nick Farrant.

Once the data is acquired, it is transferred and analysed. These analysis algorithms use big data and artificial intelligence applications, utilising techniques such as neural networks. If abnormal behaviour is detected, engineers and analysts will confirm the behaviour, and produce a diagnosis and prognosis. From this point, maintenance is planned, usually within a few flights. This type of maintenance removes the need for constant maintenance which the engine may not need, and improves safety it the quality of the engine declines faster than normal. Thus it increases business efficiency and decreases costs for both the airline and Rolls-Royce, translating to decreased operation cost, lower prices for consumers, resulting in a more attractive business.

As the distributed manufacturing network is emerging and widely adopted in the Industry 4.0. Smart and agile mini-factories are becoming more and more applicable. For this type of factory, a practical case was given to model the smart factory (Rauch et al., 2017). In the Industry 4.0, it is estimated that IoT potentially could create annual economic benefits around USD $3.9 trillion to 11.1 trillion by 2025 (Gu et al., 2016). So that large number of companies could be benefited from advanced technologies. An elevator industry was investigated to show how IoT technologies could shift paradigm to service-dominant logic using some real-life applications (Lai et al., 2017). Another important applicable topic is digital twin which could be used in smart factory so that
physical objects could be controlled through cloud-based applications. An advanced smart factory with synched factory twins was reported with a real case which used factory twin approach for synchronised digital and real factories (Pfouga et al., 2018). Therefore, traditional manufacturing factories could be upgraded and transformed into a smart level which is real-time controlled and managed.

General Electric’s Durathon battery factory is another such company that has achieved success by adopting IoT and CPS within their manufacturing process (Stephenson, 2014). The factory incorporates over 10,000 sensors on the assembly line, with additional sensors within the batteries themselves. This allows managers to know the entire state of the assembly line, products, and machinery in real time, as opposed to aggregating manually entered data at the end of the day or cycle. This can cut operating costs and resource use. All information generated can also be shared, and expert analysis and maintenance can even be done offsite by looking at the data and having a local engineer execute the actions. It should be noted that the plant has since closed down, not due to the intelligent strategies it employed, but rather due to the early developmental phases of sodium ion batteries it was producing and its low demand (St. John, 2015).

5 Conclusions

Industry 4.0, well-known as ‘smart factory’, was proposed in Germany with the modular structured smart factories, IoT, and other technologies for creating a virtual version of the physical world so as to make decentralised decisions (Lee et al., 2015). Modern manufacturing sites such as factories, assembly lines/stations, shop floors are suffering from lack of data collection since paper and manual-based systems are widely used. This paper reviews the current IoT for manufacturing in terms of key technologies and world-wide movements. IoT-enabled manufacturing is about creating an environment where all available information from within the plant floor is captured in real-time, made visible and turned into actionable insights. It involves all aspects of business, blurring the boundaries among plant operations, supply chain, product design and demand management. Enabling virtual tracking of capital assets, processes, resources and products, IoT-enabled manufacturing gives enterprises full visibility which in turn supports streamlining business processes and optimising supply and demand.

Some key technologies and world-wide applications are reviewed so that some critical insights and lessons could be obtained. Such important insights could be used for guiding practitioners and academia in their applications and research in the near future due to the development of Industry 4.0.

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