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Social Internet of Industrial Things for Industrial and Manufacturing Assets [★]

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Abstract: The IoT (Internet of Things) concept is being widely discussed as the major approach towards the next industry revolution - Industry 4.0. As the value of data generated in social networks has been increasingly recognised, the integration of Social Media and the IoT is witnessed in areas such as product-design, traffic routing, etc.. However, its potential in improving system-level performance in production plants has rarely been explored. This paper discusses the feasibility of improving system-level performance in industrial production plants by integrating social network into the IoT concept. We proposed the concept of SIoIT (Social Internet of Industrial Things) which enables the cooperation between assets by sharing status data and optimal operation and maintenance decision-making via analysis of these data. We also identified the building blocks of SIoIT and characteristics of one of its important components - Social Assets. Related existing work is studied and future work towards the actual implementation of SIoIT is then discussed.

Keywords: Internet of Things, Social Media, asset management, condition-based maintenance, decision support, system performance optimisation

1. INTRODUCTION

The importance of asset management has gradually been recognised by the world of manufacturing. Effective asset management is key to reducing the total cost of asset ownership while improving machine availability, guaranteeing security, and increasing productivity.

Condition-based maintenance, as a major element in asset management, has gained popularity over traditional corrective maintenance and preventative maintenance, especially for high-capital equipment. Despite its advantage over conventional maintenance strategies, current condition-based maintenance suffers from the following drawbacks. First, the maintenance task is targeted at individual assets, rather than the interconnected fleet of assets utilised in manufacturing. The fact that many manufacturers outsource the maintenance and management of equipment to their respective OEMs (original equipment manufacturer) is contradictory to the end-users' predominant goal – system-level performance optimisation. Since no single organisation has total visibility over the entire system, system-level optimisation can never be achieved. Second, most maintenance policies are restricted solely to the decision making of maintenance, without considering the interaction between operation and maintenance strategies, where by an appropriate operation action may have a positive impact on maintenance plans (e.g., decreasing the load for a downstream machine whose condition is deteriorating, thus providing more time for maintenance preparations). Third, even if data is shared between different assets, there is still a great reliance upon human experts to analyse the data, spot latent problems, and propose solutions, in turn dragging down system efficiency. However, a potential solution to these problems is likely to emerge from current trends in technology advances. The notion of SIoT (Social Internet of Things), which results from integrating Social Media into the IoT (Internet of Things), has been increasingly witnessed in application areas such as product-design and traffic routing. It can be reasonably considered as a tool of support for the manufacturing world.

This work attempts to explore the possibility of applying SIoT to industry to develop an industrial system performance management infrastructure allowing for machine data sharing and analytics to support asset and operations management.

In section 2 a more detailed description of the emerging trends of integrating the IoT and Social Media, as well as its recent applications will be presented. Section 3 discusses possible applications of the IoT and Social Media in industry, along with its potential advantages. The concepts of SIoIT (Social Internet of Industrial Things) and Social Assets are also presented in this section. Subsequently, section 4 defines the characteristics of Social Assets, while section 5 outlines the building blocks for SIoIT. A literature review of existing work is provided in Section 6, followed by a discussion on future work in Section 7, and a concluding section.

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2. SOCIAL MEDIA AND THE IOT

The term IoT was first coined in 1999 by The Auto-ID Labs, within the context of supply chain management enabled by RFID (radio-frequency identifications) technology. However, its current definition has been extended to include a dynamic global network infrastructure with self-configuring capabilities, where physical and virtual things have identities, physical attributes, and virtual personalities, use intelligent interfaces, and are seamlessly integrated into the information network (Kranenburg, 2006). Vast amounts of data are generated and shared across the IoT which with the support of Social Media, has been widely used in the consumer world to benchmark and optimise the product quality and customer experience. For instance, companies like Garmin and Nike provide platforms for consumers to share and compare exercise data collected via GPS-enabled wristbands and smartphones.

The notion of incorporating social elements to the IoT has been around for approximately a decade, leading to the development of SIoT. One of the early ideas associated with SIoT is “Blogject”, a neologism meaning “things that blog”. An example was a flock of pigeons that were equipped with telematics for wireless communication, a GPS device for track tracing, and sensors to record the content of air pollutants (Bleecker, 2006) . The potential of combining social and technical networks has also been tested on service provision to both human users and technical systems. A use-case of a socio-technical network – The Cognitive Office, was reported, where Twitter was chosen as an example online social network for objects in a smart office to post events from selected sensors and listen for Tweets from other devices (Kranz et al., 2010). The exploitation of SIoT can also be found in traffic routing problems, such as opportunistic communication enabled by social networks in dynamic traffic networks (Schurgot et al., 2012).

3. SIOIT (SOCIAL INTERNET OF INDUSTRIAL THINGS)

Modern industrial assets are equipped with an array of sensors monitoring their condition and operational status, generating large amounts of data. The rise of data collection and analytics in SIoT has naturally progressed to discussions in the context of industrial plants – SIoIT. In SIoIT, intelligent machines with social properties, namely, Social Assets, share status information and cooperate via a social network to achieve a common goal - optimal system-level performance.

Several scenarios can be envisioned where SIoIT is likely to enhance system performance. With SIoIT, individual machines can provide status updates to the social network, thus sharing their condition and operation status with other machines that subscribe to the network. Consider a mining operation site that consists of a variety of capital-intensive equipment (e.g., trucks, loaders, crushers, and conveyors) manufactured by different companies but interconnected through a social network. A crusher can decrease its speed to reduce downstream loads, thus helping the conveyor whose condition is excessively deteriorating at the current loading level (alternatively, the crusher can send a message to the human operator elaborating the problem and suggesting a possible solution, such as slowing the crusher down). In addition, assuming a truck has experienced a sudden break-down because of gear failure. This truck will be able to send a warning message to another truck at a remote site with gears from the same batch. Instead of passively waiting for instructions, machines actually actively participate in the production process.

The possibilities for machine learning and optimisation are significant in a world where machines in factories all over the world collect, update, and share status data via a social network. SIoIT enhances industrial data analysis and performance management at three levels – machine, production plant, and network levels. At the machine level, benchmarking data is available for manufacturers to analyse machine reliability and associate the root causes of differences in performance. At the production plant level, an overall visibility enabled by machines updating status to the social network will help manufacturers spot bottleneck in the system. Thus, system-level optimal reliability, productivity, and energy consumption can be achieved. In addition, intelligent machines are equipped with the ability to cooperate and learn from each other as a means to identify the best practice for problem solving. Understanding what and how other machines are doing makes it possible for machines to advise each other on collectively achieving production goals, as well as adjusting its own behaviour for a long-term optimal system cost-risk-performance balance. At the highest level, the network level, with more data generated and more machines taking part in the social network, comprehensive predictive analytics and learning will be realised, benefiting OEMs, designers, and service providers. Moreover, with intelligent machines looking after the system and themselves, spotting latent risks and executing solutions or suggesting solutions to human operators, the efficiency of maintenance is greatly increased.

In the future world of manufacturing, intelligent machines will communicate and cooperate with each other via a social network to accomplish production tasks, which very much resembles the human society.

4. CHARACTERISTICS OF SOCIAL ASSETS

The very first architectures of the IoT are based on the success of RFID technology. While this approach is ideal in tracking physical objects within a confined space, it is insufficient for more flexible and complex scenario requirements. This has led to an alternative architectural model – a loosely coupled, decentralised system of Smart Objects (Kosmatos et al., 2011). Smart Objects, which are autonomous physical/digital objects augmented with sensing, processing, and network capabilities, are categorised into activity-aware, policy-aware, and process-aware objects, and are believed to be building blocks for the IoT to cater functional needs (Kortuem et al., 2010). Similarly, what it takes for objects to be ‘smart’ still applies to the basic components for SIoIT in the manufacturing domain (i.e., machines or assets). However, it requires an additional requirement – apart from being ‘smart’, these components also need to be ‘social’.

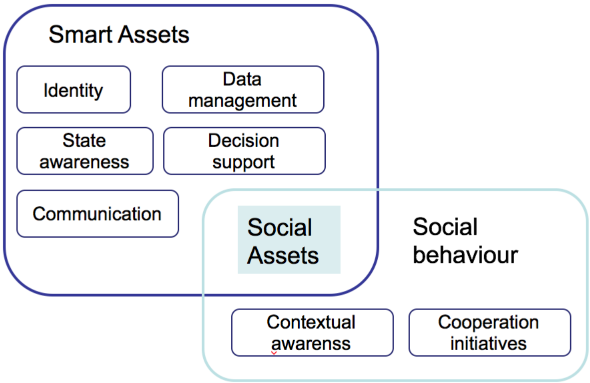

Fig. 1. Fundamentals for Smart Assets and Social Assets

The fundamental properties that Smart Assets are supposed to possess can be adapted from the five characteristics of Smart Products/Objects proposed in the new generation of object-centric industrial paradigm (Sánchez López et al., 2012). Smart Assets are those that encompass following properties

Identity - A unique identity is needed for the Smart Asset to be tracked, recorded, and referred to in the system.
State awareness - Smart Assets should be able to sense its own operating status and measure performance indexes, such as vibration, temperature, and concentration of a particular chemical element.
Communication - They should be capable of exchanging information with other Smart Assets, OEMs, as well as human operators.
Data management - It is necessary to classify and store measurements possibly made by sensor transducers associated with the assets, while removing some history data, if appropriate.
Decision support - Smart Assets should have a decision support mechanism to generate apt actions in response to different situations that have arisen. Moreover, they should be able to exhibit opportunistic, goal-directed behaviour and act proactively.

In order for machines to cooperate, as a means to optimising system-level performance, two more requirements are proposed to transform Smart Assets into Social Assets – contextual awareness and cooperation initiatives, as shown in Fig. 1.

Contextual awareness - A piece of asset with contextual awareness not only investigates its own status, but also perceives its environment, in which they are situated and which may be the physical world, a user, a collection of other assets, or the Internet (Fortino et al., 2012). They should have an understanding of the consequence of any action it takes that might cause changes to the surroundings. Contextual perception implies understanding of a problem domain much broader than a single asset could comprehend, thus enabling the asset to act more wisely.
Cooperation initiatives - Planting cooperation initiatives into assets is considered necessary in manufacturing systems for two reasons. First, the local goals of a single asset are very likely to be contradictory to the goal of a plant manager or another asset (e.g., two machines push production tasks to each other so as to avoid deterioration and wear and tear while the plant manager wants maximum productivity). If assets are open for cooperation, these conflicts can be resolved through exchange of knowledge, negotiation between machines, and collective decision making. Second, just as humans help and give advice to each other, through cooperation initiatives, assets will be inclined to recommend each other the best possible action path to take for the asset itself, as well as for the overall improvement of system-level performance.

5. BUILDING BLOCKS FOR SIOIT

While Social Assets act as the main building block, other components should also be added during the actual implementation of SIoIT. The building components of SIoIT and their function blocks are shown in Fig. 2. A detailed description is given as follows:

Social Assets - A software agent is assigned to each asset, augmenting it with intelligent and social behaviours. These assets should be actively engaged throughout the production process. Specifically, Social Assets should be able to carry out:
(1) self-monitoring, diagnostics, and prognostics: machine performance data obtained by sensors should be collected and analysed by the machine, in order to evaluate current status, spot potential failure, and predict future status;
(2) relationship analysis: by analysing data, consulting experts, and other possible means, Social Assets should find the relationship between a single asset and the performance of other assets as well as the whole system;
(3) selection of data of interest: selecting and posting relevant data on the social network, as well as subscribing itself to data that may be of self-interest.

Social network platform - A social platform is where the actual social behaviours of assets occur. It should be equipped with necessary hardware and software to function as a channel for:
(1) general communication: allowing machines to post their RUL, operation data, and events planned (e.g., production tasks and maintenance tasks). It should also enable the subscription of an individual asset to information that is of its own interest. M2M (machine-to-machine) communication, whereby machines seek help from and give advisory to each other, should be realised on the platform;
(2) resource administration: in charge of documenting the information of any asset that has joined or left the social network, including its unique identification, subscription status, and functions, thus providing a directory service;
(3) data storage and management: storing data that has been shared on the platform in an efficient manner, and deleting data which is out of date or of no value;
(4) negotiation: providing a mechanism for negotiation between machines to resolve conflicts and reach common goals.

Protocols and ontologies - Protocols are needed to guarantee a unified data transport format while ontologies provide a mutually understandable communication context, allowing all participants in the conversation to perceive the shared information in the same way. The contents of this building block includes the following:
(1) domain-specific ontologies: since the context of the

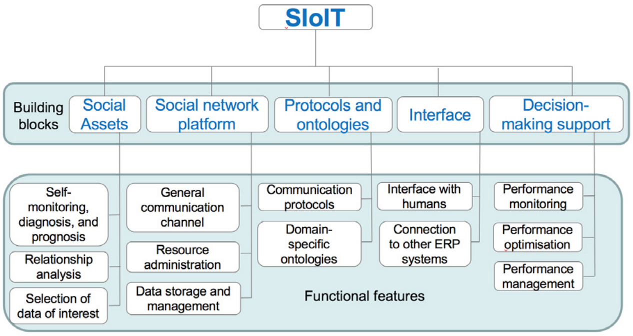

Fig. 2. SIoIT building blocks, their functional features, and the mapping between existing research and technologies

proposed SIoIT is industrial plants, the ontologies include formal naming and definition of the types, properties, and interrelationships of the entities that fundamentally exist for the production and maintenance domain;
(2) communication protocols: the protocols are dedicated to information exchange between assets as well as different layers of the SIoIT architecture.

Interface - An interface is needed for data sharing with other ERP systems, and human operators. Among aspects that should be taken into consideration are:
(1) interaction with humans: although under the most ideal situation, assets process data, make decisions, and take actions on their own, an interface should still exist for information exchange and interaction between the machines and human operators, such as receiving parameter inputs, getting commands, sending alert messages, and suggesting actions;
(2) connection to other ERP systems: as the job shop where all machines reside is not independent of other resources of an enterprise, it is necessary to have information exchange with other ERP systems regarding service, finance, and logistics;

Decision-making support - A series of decision-making support functions as listed below should be available for the purpose of system-level performance optimisation. However, it still remains to be explored whether the function should reside in individual assets, at a supervisory level, in a hybrid combining these two, or through other manners. These decision-making support functions include:
(1) performance monitoring: Production data (e.g., machining status, product information, and maintenance schedules), is made available by the social platform and can be used by the performance monitor to assess individual asset performance and system performance. Through data analytics, the performance monitor will attempt to identify the bottleneck of the manufacturing plant. At a higher level, with information obtained by connecting with services, logistics, financials, and other relevant data base of the organisation, potential risks to the organisation's objectives can be identified;
(2) performance optimisation: The purpose of the performance optimiser is to generate action plans regarding maintenance and operation that will potentially bring better system-level performance based on data analytics results provided by the performance monitor. The consequent system management plans are then passed on to the performance manager for further consideration;
(3) performance management: The major function of performance management is to select the best system management plan proposed by the performance optimiser based on a variety of criteria. The chosen plan will be posted on the social network platform, which will then be implemented by machines who have subscribed to this thread of message, and are concerned in the optimised system management plan.

6. STATE OF THE ART

A significant amount of research has been conducted on both the technical and modelling aspects of what forms a SIoIT, some of which will be reviewed in this section.

With RFID technology as a major breakthrough for automatic identification, it has become feasible to assign a unique ID, residing in a tag to every object, while keeping track of it. Additional data such as manufacturer, product type, and delivery date can also be incorporated in the tag (Want, 2006). Although RFID systems track objects in real-time, allowing for mapping of the the real world into the virtual world, its capacities in providing the continuously changing condition information of the objects are very limited.

At the same time, sensor technologies have emerged to remove the limitation of RFID. As sensor technology becomes cheaper and more mature, most new generation machines are equipped with sensors as part of its embedded control/computing systems, enhancing its ability to sense the real-world condition. Research aiming at seamlessly integrating sensor nodes into the Internet has led to the area of WSN (Wireless Sensor Networks), which has realised real-time information exchange between machines and other entities on the Internet. The integration of passive RFID tags and sensing technologies has made possible an energy-efficient and passively-powered sensing platform for condition monitoring and data collection (Sample et al., 2007).

As RFID and WSN for objects tracking and communication, research efforts have also been dedicated to developing an overall architecture linking the physical objects to the digital domain to manage their information, communication, relationships, and functions - middleware technologies, or SOA (service-oriented architecture). Middleware is a software layer or a set of sub-layers interposed between the technological and the application levels, which simplifies the development of new services and the integration of legacy technologies into the new ones. IoT architectures that utilise SOA have been intensively studied in recent years. For instance, a generic architecture for IoT with five layers (perception, network, middleware, application, and business layers) was proposed (Khan et al., 2012). In addition, a gateway centric IoT architecture was developed to enable real-time interaction between mobile clients and smart objects through a wireless gateway (Datta et al., 2014).

Another branch of research has been dedicated to communication standards and protocols for information exchange between Smart Objects, as well as different layers of the IoT architecture. The IPSO (IP for Smart Objects) Alliance was formed in 2008 to promote the use of IP (Internet Protocol) in the IoT on the grounds that IP has all the properties needed for the IoT (Dunkels, 2008). A modified version of IPv6 called 6LoWPAN intended for low-power embedded devices has been designed (Mulligan, 2007). Internet ∅ takes a similar view and simplified the current IP to adapt it to make objects visible and tractable anywhere at any time (Gershenfeld et al., 2004).

Apart from work on communication protocols, research has also been dedicated to the development of domain-specific ontologies which provide context awareness to any participant involved in the information exchange process. Vermaak and Kinyua (2007) developed an ontology using OWL[1] (Ontology Web Language) for a component-handling platform. An application-specific ontology has been generated using Protégé semantic editor[2] for the wood processing factory as part of the knowledge base for an agent-based decision support system(Elghoneimy and Gruver, 2012).

Ubiquitous computing has been a popular trend for over a decade. Its underlying technology, embedding microprocessors in everyday objects, meets the hardware requirements where objects can be augmented with intelligence in the IoT sense. Moreover, the MAS (multi-agent system) approach has proved to be an appropriate software engineering paradigm for Smart Objects. The characteristics of software agents fit perfectly into the description of a Smart Object, including (Wooldridge and Jennings, 1995):

Autonomy - Agents should have a degree of control over themselves without direct interventions of superior entities.
Social Ability - Agents should have interactions with other agents and humans to perform their tasks or offer help, as necessary.
Responsiveness - Agents should be able to perceive the environment in which they are situated , while responding promptly to condition changes.
Proactiveness - Instead of only responding to the environment, agents should exhibit goal-directed behaviour and take initiatives when needed.

MAS application can be found in fields such as transportation, logistics, and graphics. Here, a brief review of the implementation of MAS in maintenance and production control is given. Ghonaim et al. (2011) proposed an agent model that blends flexible manufacturing with distributed intelligence in the form of smart tag and resource agents. JADE (Java Agent Development Environment) was utilised as host for the smart controller layer. Bouzidi-Hassini and Benbouzid-Sitayeb (2013) has formulated a joint production and maintenance scheduling MAS model that takes into accounts for human resource availability. A MAS-based model for Intelligent Control-Maintenance-Management System (ICMMS) was developed in order to realise the integration of control, maintenance, and technical management of production process automation system (Fu et al., 2004). The negotiation between agents has mostly been achieved through CNP (Contract Net Protocol) (Smith, 1980) or the variations of it.

There is also a significant amount of work devoted to the condition-based maintenance of a single asset. Liang and Parlikad (2015) proposed a mathematical condition-based maintenance model for complex industrial assets with accelerated deterioration caused by fault propogation. Wu et al. (2007) developed a decision support system for predictive maintenance of rotational equipment by using neural network in the modelling. Djurdjanovic et al. (2003) developed an infotronics-based prognostic prognostics tool called the Watchdog Agent for product performance degradation assessment and prediction, capable of recognising faults by memorising significant signature patterns.

7. FUTURE WORK

While the underlying technologies of integrating social networks into the IoT are mostly in place, several aspects are still left for exploration to enable SIoT to improve system performance.

As discussed in the previous section, the hardware and software for knowledge and information sharing within a network has both been intensively studied. However, there remains a lack of research on linking the performance of a single machine to the performance of other machines, as well as the whole system. Moreover, there is no specification on what data assets should share with the social network or what contents assets should subscribe to. In other words, the problem of how to define useful information for production systems and single assets still remains unsolved. Additionally, while protocols exist for information sharing across a network, specific requirements for definition of contents used for status sharing between machines may rise in the manufacturing domain, in turn leading to the need for a different ontology.

Apart from the aforementioned technical challenges, little or no research efforts have been devoted to developing a decision support system, which explores machine status data shared on a social network platform for the purpose of system-level performance optimisation. Specifically, while machine data obtained from sensors have been broadly used to analyse single machine behaviour, models for learning system behaviour from the share data is generally lacking. In addition, no attempt has been made to attain better system performance via appropriate operation strategies (e.g., where a machine with better condition shares the load of a deteriorating machine). One last aspect that requires more research efforts is maintenance plans. As the system state is continuously evolving, an approach is needed to dynamically generate optimal maintenance plans, taking into consideration both individual asset condition and system service level requirements.

Future research direction should work towards: (1) designing and implementing the system architecture for SIoIT supporting the vision of cooperating machines based on use-cases in industry; (2) developing a performance management system that enables analysis of data shared by assets through the social network platform to support optimal operation and maintenance decision-making.

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[1] http://www.w3.org/TR/owl-ref/

[2] http://protege.stanford.edu

8. CONCLUSION

The paper discussed the feasibility of improving system-level performance in industrial plants by integrating Social Media into the IoT. The concept of a performance management system called SIoIT was proposed, enabling cooperation between assets by sharing status data, as well as optimal operation and maintenance decision-making via data analysis. A brief literature review regarding the IoT, multi-agent systems, and condition-based maintenance was provided to help spot research gaps between state of the art and the realisation of SIoIT. It has been identified that the focus of any future work should focus on designing and implementing a system architecture for SIoIT, based on use-cases in industry and the development of a performance management system with decision support functions.

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REFERENCES

Bleecker, J. (2006). A manifesto for networked objects – cohabiting with pigeons , arphids and aibos in the Internet of Things. In *Proc. of the 13th International Conference on Human–Computer Interaction with Mobile Devices and Services, MobileHCI*, 1–17.

Bouzidi-Hassini, S. and Benbouzid-Sitayeb, F. (2013). Multi-agent based joint production and maintenance scheduling considering human resources. *2013 5th International Conference on Modeling, Simulation and Applied Optimization, ICMSAO 2013*, 0–4.

Datta, S.K., Bonnet, C., and Nikaein, N. (2014). An IoT gateway centric architecture to provide novel M2M services. *2014 IEEE World Forum on Internet of Things (WF-IoT)*, 514–519.

Djurdjanovic, D., Lee, J., and Ni, J. (2003). Watchdog Agent - an infotronics-based prognostics approach for product performance degradation assessment and prediction. *Advanced Engineering Informatics*, 17(3-4), 109–125.

Dunkels, A. (2008). The Internet of Things : IP for Smart Objects. Technical report, IPSO Alliance.

Elghoneimy, E. and Gruver, W.A. (2012). Agent-based decision support and simulation for wood products manufacturing. *IEEE Transactions on Systems, Man and Cybernetics Part C: Applications and Reviews*, 42(6), 1656–1668.

Fortino, G., Guerrieri, A., Russo, W., Bucci, V.P., and Cs, R. (2012). Agent-oriented Smart Objects development. In *Computer Supported Cooperative Work in Design (CSCWD), 2012 IEEE 16th International Conference on*, 907–912. IEEE, Wuhan.

Fu, C., Ye, L., Liu, Y., Yu, R., Iung, B., Cheng, Y., and Zeng, Y. (2004). Predictive maintenance in intelligent-control-maintenance-management system for hydroelectric generating unit. *IEEE Transactions on Energy Conversion*, 19(1), 179–186.

Gershenfeld, N., Krikorian, R., and Cohen, D. (2004). The internet of things. *Scientific American*, 291(4), 76–81.

Ghonaim, W., Ghenniwa, H., and Shen, W. (2011). Towards an agent oriented smart manufacturing system. *Proceedings of the 2011 15th International Conference on Computer Supported Cooperative Work in Design, CSCWD 2011*, 636–642.

Khan, R., Khan, S.U., Zaheer, R., and Khan, S. (2012). Future internet: The Internet of Things architecture, possible applications and key challenges. *Proceedings - 10th International Conference on Frontiers of Information Technology, FIT 2012*, 257–260.

Kortuem, G., Kawsar, F., Sundramoorthy, V., and Fitton, D. (2010). Smart Objects as building blocks for the internet of things. *IEEE Internet Computing*, 14, 44–51.

Kosmatos, E.A., Tselikas, N.D., and Boucouvalas, A.C. (2011). Integrating RFIDs and Smart Objects into a unified Internet of Things architecture. *Science*, 2011(April), 5–12.

Kranenburg, R.V. (2006). *The Internet of Things: a critique of ambient technology and the all-seeing network of RFID*, volume 4.

Kranz, M., Roalter, L., and Michahelles, F. (2010). Things that Twitter: social networks and the Internet of Things. *What can the Internet of Things do for the Citizen CIoT Workshop at The Eighth International Conference on Pervasive Computing Pervasive 2010.*

Liang, Z. and Parlikad, A.K. (2015). A condition-based maintenance model for assets with accelerated deterioration due to fault propagation. *IEEE Transactions on Reliability*, 64(3), 972–982.

Mulligan, G. (2007). The 6LoWPAN architecture. *Proceedings of the 4th workshop on Embedded networked sensors - EmNets '07*, 78.

Sample, A., Yeager, D., Powledge, P., and Smith, J. (2007). Design of a passively-powered, programmable sensing platform for UHF RFID systems. *RFID, 2007. IEEE International Conference on*, 149–156.

Sánchez López, T., Ranasinghe, D.C., Harrison, M., and McFarlane, D. (2012). Adding sense to the Internet of Things: an architecture framework for Smart Object systems. *Personal and Ubiquitous Computing*, 16(3), 291–308.

Schurgot, M.R., Comaniciu, C., and Jaffr, K. (2012). Beyond traditional DTN routing : social networks for opportunistic communication. (July), 1–8.

Smith, R.G. (1980). The contract net protocol: high-level communication and control in a distributed problem solver. *IEEE transactions on Computers*, C-29(12), 1104–1113.

Vermaak, H. and Kinyua, J. (2007). Multi-agent systems based intelligent maintenance management for a component-handling platform. *2007 Ieee International Conference on Automation Science and Engineering, Vols 1-3*, (November 2015), 709–714.

Want, R. (2006). An introduction to RFID technology. *IEEE Pervasive Computing*, 5(1), 25–33.

Wooldridge, M. and Jennings, N.R. (1995). Intelligent agents: theory and practice.

Wu, S., Gebraeel, N., Lawley, M., and Yih, Y. (2007). A neural network integrated decision support system for condition-based optimal predictive maintenance policy. *Systems, Man and Cybernetics, Part A: Systems and Humans, IEEE Transactions on*, 37(2), 226–236.