Secure Information Sharing in an Industrial Internet of Things

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Abstract—This paper investigates how secure information sharing with external vendors can be achieved in an Industrial Internet of Things (IIoT). It also identifies necessary security requirements for secure information sharing based on identified security challenges stated by the industry. The paper then proposes a roadmap for improving security in IIoT which investigates both short-term and long-term solutions for protecting IIoT devices. The short-term solution is mainly based on integrating existing good practices. The paper also outlines a long-term solution for protecting IIoT devices with fine-grained access control for sharing data between external entities that would support cloud-based data storage.

Index Terms—Industrial internet, Internet of Things, secure information sharing, access control, roadmap

I. INTRODUCTION

The Industrial Internet describes industrial processes controlled by SCADA systems and similar that are being networked and interconnected across the value chain to create smart integrated production systems. The Industrial Internet phenomenon embraces the Internet of Things (IoT) domain, where smart production based on RFID tagged products and sensor networks are being integrated into an Industrial Internet of Things (IIoT). This allows for improving the quality, traceability and integrity of industrial processes by allowing better modeling of the Cyber-Physical Systems (CPS) and processes using techniques such as data mining, big data analysis, learning systems and knowledge-based systems using semantic modeling and ontologies.

It also improves maintainability, reliability and availability of the controlled industrial processes by using sensor networks for Condition-Based Maintenance (CBM) in order to monitor wear and pre-failure of technical components. This reduces the risk of system breakdowns during production, and allows for planned exchange or upgrade of production equipment with lower risk of excessive downtime during repairs.

The most important actors considered in this article are:

- Industrial organisations that want to introduce Internet of Things (new markets).
- Industrial organisations that require secure exchange of information related to IoT or need information related to their supplied equipment.
- Third party organisations that require limited access to some of the sensor data, for example vendors providing sensor or equipment maintenance or managed security service operator equipment.

An important objective for manufacturers is to improve the production efficiency whilst reducing planned and unexpected downtime. IoT may help to achieve this goal, however in order to do this, any efficiency improvements must be measurable. The Overall Equipment Effectiveness (OEE) is a well-known metric of manufacturing efficiency that can be used for this. It is defined in terms of the availability $A$, performance efficiency $P$ and quality rate $Q$ as $OEE = A \cdot P \cdot Q$.

A problem with OEE, is that it in itself is not sufficient, since it only provides the status of production efficiency, and blurs the relationship between performance and cost involved in sustaining a given OEE level [1]. It does for example not show the relationship between invisible pre-failure and wear conditions and the production performance. Furthermore, when a device eventually has failed, possibly interrupting production, then this will already have caused a loss in production efficiency.

Data mining from condition-based maintenance monitoring sensors is therefore one area where production companies can improve productivity beyond what OEE easily can measure. This allows for performing predictive fault analysis and control functions in order to provide more resilient effectiveness [1].

IoT systems helps in laying the foundations for such predictive manufacturing by providing the essential structure of smart sensor networks and smart machines [1]. Communication protocols, such as the Object Linked Embedded for Process Control, Uniformed Architecture (OPC-UA) facilitate platform independent data acquisition from these sensors using a Service Oriented Architecture (SOA) based on web services [2]. OPC-UA also supports vertical integration between different layers of factory automation, such as Enterprise Resource and Planning (ERP) systems for factories, Manufacturing Execution Systems (MES) and automation systems [2].

It even supports integrating data with systems in partner companies, as illustrated in Figure 1. Security, reliability and AAA (Authentication, Authorisation and Accounting) are also integrated into the OPC-UA standard, which supports an API mapping to XML web services focusing on interoperability as well as an UA native mapping focusing on efficient low-bandwidth data transfers [2].

The core characteristics that typically identifies IoT devices, such as smart sensors are:

- Interaction with the physical world
• Have communication capabilities (device to person, devices to device, and device to multiple devices)
• Have some processing capabilities (e.g. support decision making)

The market for IoTs is believed to be rapidly increasing as services utilising widely deployed sensor networks become generally available, such as smart home equipment, smart cars etc. at the same time as any device now typically will have the capability of being networked. This means that there will be a large amount of mass-produced and affordable sensor technologies that can be deployed everywhere, including in industries.

This means that the production equipment in manufacturing is becoming more and more advanced and smarter by supporting inherent abilities for decision making. However, both operation and maintenance require expert knowledge, and often it will be external parties that have this knowledge. There will therefore be a need for secure information sharing and collaboration among stakeholders, as illustrated in Figure 1.

The figure shows that the company often will collaborate with several third parties, for example external vendors or entities who will get access to some data from industrial IoT devices inside the company. Examples of such devices are: intrusion detection appliances as part of a managed security service; vendors, suppliers or trusted third parties managing custom sensors for monitoring vibration, wear or temperature for Condition-Based Maintenance (CBM) as well as flow, temperature, pressure or position in IIoT devices controlling industrial process etc.

The main problem is that all these actors need access to their devices, but should only have access to these according to a strict definition of need, ensuring minimal spillover of other company sensitive information about production processes etc. as possible. Furthermore, not only the device, but also the data and information generated by the device will need to have constraints in the form of detailed access control, especially in multi-sensor devices.

The scenario furthermore shows that the company is performing data analysis, potentially using big data from several manufacturing plants, in order to extract necessary indicators on production quality while also analysing pre-failure and wear based on the CBM sensors. Another example is analysing for signs of cyber-attacks on either the corporate or process network. External vendors may then be notified if anomalous data are detected, so that these then can do further troubleshooting via an interface towards the sensors they are authorised to manage.

There is also a security and safety risk with such external parties, since it increases the amount of people who will have potentially deep access into industrial control networks. This increases the risk of someone disrupting industrial processes if they have malicious intent. Not the least will there be a push towards outsourcing internal services, for example ERP systems, to cloud service providers, which adds additional challenges when it comes to managing the services securely.

In 2020, 25 billion connected things in use: http://www.gartner.com/newsroom/id/2905717

Figure 1. High-level figure illustrating the problem with data sharing of sensor data for industrial processes.

as well as reducing the risk for leakage of corporate private material.

Protecting data transmissions in a secure manner is technically relatively easy to achieve using existing and standardised cryptographic methods such as Transport Layer Security/Secure Sockets Layer (TLS/SSL) or Datagram Transport Layer Security (DTLS). However a challenge is managing and provisioning keys and digital certificates as well as handling user and service authorisation in a scalable and manageable way.

The main problem is that current solutions for managing access in general are too coarse-grained. Firewall rules will for example give access to the entire CBM or process control network without limiting access to the sensors and the data that external parties are allowed to access, especially when the data is mixed.

This paper discusses how security can be improved in industries wanting to utilize the power of IoT, especially focusing on how different stakeholders such as customers, subcontractors and equipment suppliers can be granted access to sensor data and other data from the manufacturing process in a controlled and secure manner, without compromising sensitive data that are not shared.

The rest of this paper is organised in the following manner: Section 2 presents the background of industrial IoT, while their requirements are further explained in section 3. The current challenges is explained in section 4. Section 5 presents relevant cases from the industry and section 6 gives an insight into relevant standards. We present a short term solution that can improve the current security in section 7, while section 8 elaborates on the possible long term solutions which could be applied for a more secure and trustworthy IoT. Current existing research is presented in section 10, Related Work. Section 11 discusses and summaries the paper, while the last section; section 12 gives an overview towards possible future
II. BACKGROUND

New technology and availability of affordable mass-produced sensors and devices enable new possibilities to meet requirements for continuous improvements of productivity and efficiency.

The industry looks at IoT and digitalisation of sensors as part of Industry 4.0 and sees them as tools to improve productivity and reduce costs, e.g. through CBM. Low-cost sensors with good enough precision and lifetime enable more detailed process insights, and better process optimization.

With the ever increasing capabilities of computing hardware, new technology will cost less and become more readily available. Small sensors with the ability to be interconnected into the Internet, enables a plurality of new possibilities. In an industry setting, this could provide a reasonable and efficient way to gather more information of the production process giving new opportunities for optimisation. Easy sensor deployment increases the potential for cloud based data mining and analytics using big data from semantic sensor networks, virtual sensors and complex event processing [3].

A. The Industry 4.0 Challenge

The term industry 4.0 (Industrie 4.0) is a German strategic initiative for strengthening the competitiveness of the German manufacturing industry based on an association of representatives from business, academia and politics [4]. Similar ideas have approached also outside the German area, such as Industrial Internet, Advanced Manufacturing, Integrated Industry and Smart Industry [5].

There has so far not been any clear definition of what Industry 4.0 is, however a meta-study of 200 publications describing the concept was done by Hermann et al., who came up with the following definition of Industry 4.0 [5]: Industrie 4.0 is a collective term for technologies and concepts of value chain organization. Within the modular structured Smart Factories of Industrie 4.0, CPS monitor physical processes, create a virtual copy of the physical world and make decentralized decisions.

Over the IoT, CPS communicate and cooperate with each other and humans in real time. Via the Internet of Services (IoS), both internal and cross-organizational services are offered and utilized by participants of the value chain.

Security is a challenge with IIoT and Industry 4.0, where heavily interconnected production systems exchange information and data, not only within the manufacturing facility, but also across the value chain to corporate Enterprise Resource and Planning (ERP) systems, customers, subcontractors and equipment suppliers. One large problem with IIoT, is that it is integrated with the control systems of existing production facilities which may have a lifetime of decades and was originally built without security or Internet connectivity in mind.

The security of control system protocols have also lagged behind the security of information technology (IT) systems, and is only now starting to get more widespread use. This means that many devices, which were never intended to be networked, may be interconnected in an IIoT setting. This creates a huge attack surface towards devices that may not be able to protect neither the data integrity nor data confidentiality as well as frequently having weak access control mechanisms, like requiring default user names or passwords [6], [7]. Cars or airplane systems are examples of such real-time systems where critical systems often share the same information bus, which makes it highly dangerous if one device has malicious behavior.

III. INDUSTRIAL INTERNET OF THINGS REQUIREMENTS

There are several important requirements that an infrastructure handling industrial IoT devices must fulfill.

A. Real-time data transfer

Control systems typically require timely delivery of information. What is consider real-time depends on the process being controlled. The inner process control loop may need to control processes down to millisecond precision without any loss of control signals. This means that the process control network will have very limited tolerance for variations in latency which causes problems when using traditional Internet security protocols such as TLS/SSL. SSL key renegotiation would for example cause large problems for such a process, and even running such a process over TCP/IP might not be feasible. Other processes have less strict real time requirements, and will be able to run over traditional Internet links without problems.

B. Availability

It is typically a basic requirement that information is always available and accessible to authorised users and services. This is also emphasised in the OEE metric, where availability is one of the foundational metrics of service quality. Availability also implies data persistence, i.e. ensuring that data does not suddenly disappear due to failure (disks wearing out, lightening strikes etc). Another concern may be legal issues causing obstacles for data availability between countries, as
well as a concern that foreign authorities may unrightfully gain access to company sensitive information.

As industry moves towards an IoT scenario, then there will be a requirement that these data are available from everywhere and to everywhere. Data must be available both between production facilities, device suppliers as well as subcontractors and the users themselves, who will expect to be able to purchase tailor-made industrial products. The car industry is already at the front of such production by providing tailor made products according to the customers wishes. This again means that industrial data needs to be made available also via cloud-based services in order to provide the necessary scalability to handle a large customer base or for reducing the operational costs of managing IT equipment.

C. Secure information sharing

Secure information sharing implies that there exists some data that can be shared with partner organisations, or between daughter companies, while preserving data confidentiality and integrity. Existing cryptographic building blocks, such as public key encryption, symmetric encryption, message authentication codes etc. can be used for enforcing this. One of the main challenges in secure information sharing is scalable solutions for handling identities and authorizations, including protocols for managing keys, encryption protocol upgrades and digital certificates. This is also where many IoT protocols (e.g. Zigbee, ZWave etc.) have been shown to be flawed [3], [2].

Secure information sharing includes non repudiation, so that partner organisations cannot deny having done certain operations. The latter can for example be implemented using secure logging schemes [10], [11].

D. Information Leakage Detection and IPR-handling

Preventing information leakage includes data leakage detection and IPR handling, for example detecting whether process sensitive information is leaked from the owning industry, and found stored in inappropriate places. A possible solution can be using Digital Rights Management (DRM) type of technologies to limit the possibilities of data leakage by strong cryptographic access control methods to the information, as well disallowing copy/paste of this information between a trusted and untrusted application. DRM can be tied to hardware, like the Trusted Platform Module (TPM). There are already scalable solutions for decrypting quite high bandwidths today, e.g. satellite HD video etc. Limiting data access can also be done using more traditional techniques, such as limiting data access using dumb terminal servers (e.g. Citrix servers) allowing only limited access to sensitive data inside the production plant. A challenge in both of these cases, is that some data leakage still may occur, for example by taking screenshots of the terminal window or software with DRM protection, or even taking digital photographs of the screen used to present these data using external devices (cameras, mobile phones etc.). The information owner will therefore need to trust the external parties to some extent, however it is possible to limit the possibilities for other types of data analysis and data correlation than the data owner desires using such measures.

Challenges with real-time data due to network latency may be a problem in some use scenarios, however other use cases are less time critical given the latencies of encrypted traffic on the Internet.

Techniques such as digital watermarking or tagging of information can be used to enforce nonrepudiation for such data leakages [12]. It is however questionable how useful digital watermarking of sensor signals will be for sensor data, since this adds noise which may interfere with the signal quality. Another technique that has been proposed is entropy-based metrics for detecting information leakages and verifying security policies, in order to detect accidental information leakages due to faulty security or privacy policies [13].

E. Flexible production

Flexible production is at the core of the Industry 4.0 vision and implies a requirement for reconfigurability of production cells within the industry, so that these easily can be repurposed and assigned to other product lines on demand according to purchase orders. This implies that there must be tight integration between the ERP, MES and factory automation system, so that production cells can be reprogrammed, moved and assigned to the product lines where they are most urgently needed, without compromising the logistics of raw materials, dependent products and finished products.

F. Decision support

Decision support systems can be used both for planning the production, for condition-based maintenance as well as for handling logistics. Information can be mined using different data mining techniques such as data warehousing or big data analysis in combination with artificial intelligence or learning systems. Another component that frequently is used with decision support systems is ontology based reasoners that are able to infer new knowledge based on information stored in the ontology [14]. Decision support is traditionally done in-house, but can also be done distributed based on data in the cloud, for example to measure customers opinions towards the company’s products.

CBM is a typical example where third parties can have access to analysing and monitoring facilities, and can have means for requesting shutdown of equipment based on condition data.

G. Fine-grained Access Control to Data

Sophisticated access control mechanisms is in particular relevant when data is shared among multiple parties and come from a variety of sources, which is the case for typical IoToT scenarios. It has been suggested that a transition from a traditional Role-Based Access Control (RBAC) infrastructure to a more fine-grained Attribute-Based Access Control (ABAC) would be required in order to manage access to an IoT based infrastructure [3]. Attribute-based access control mechanisms, such as the eXtensible Access Control Markup Language (XACML) [15], has for example been proposed used in IoT
there are some key components that are essential to services or encryption of information. In any system, including in IIoT on the other side. What is sufficient and secure enough? on one side with the ability to share and utilize the possibilities strategy.

internet of things, among others by applying a defense in depth to best protect and prevent these attacks on an industrial impacts the attack surface. Subsequent sections describe how this section describes the main challenges that may occur when attempting to share data in an industrial internet of things scenario. The obvious challenge in an industrial setting, focusing on utilising IIoT for automation, and analytical gains is how to ensure that the introduced things are secure and tamper proof. This includes discussing the how IIoT devices impacts the attack surface. Subsequent sections describe how to best protect and prevent these attacks on an industrial internet of things, among others by applying a defense in depth strategy.

The main challenge is how to balance the need for security on one side with the ability to share and utilize the possibilities in IIoT on the other side. What is sufficient and secure enough? Security is not achieved by only implementing secure devices or encryption of information. In any system, including IIoT there are some key components that are essential to achieve a secure solution;

- Secure device
- Access control, including identity management, authentication and authorization
- Secure communication
- Management, and
- Trust

Access control can be enforced at several layers, should it be on the network, device or data layer? Access control on the data layer will give the most flexible solution, but also represent the most complex authorization scheme.

Many of the industrial sensors are furthermore resource constrained devices running real-time processes with limited processing capability, which means that traditional software security mechanisms, such as using a public key infrastructure with standard encryption mechanisms may not work due to unacceptable latencies or lack of processing capacity for example during key renegotiation. Devices tend to be made to run on exactly the minimal required hardware specification so there is little to no leverage to add security components.

Another security challenge is that device manufacturers have a bad track record when it comes to adding backdoor capabilities to their devices in order to manage or update these devices (for example [24]). The original intent for installing such backdoors may be valid enough, however the problem is that these typically use a very simple security solution - often only using a standard username/password, which obviously is not secure in today’s Internet. It is therefore important that the devices themselves also can be integrated into the organisations’ AAA infrastructure.

### A. Legacy-systems

One problem in industrial systems occurs when upgrading to a modern IIoT from an older system which did not account for global connectivity. This can lead to security issues, especially when some of the devices have not considered the possibility of appearing in a non-restricted network, when part of the control network is being bridged to other networks, which in turn may be exposed to the Internet. Another problem is that legacy systems tend to have non-differentiated networks and coarse-grained access control if any.

### B. Threats

The threat landscape is quite different across different industries and sectors. In some industries the secrecy of the processing methods are considered essential for the company existence, while other industries have completely different issues. Industries with high value IPR’s are also exposed to more advanced threat actors than industries with less IPR

The insider threat is perhaps one of the largest type of threats in an IIoT scenario, since own employees as well as vendors and others may be authorised to access and/or control sensors in the network. New functionality may be added to the control network, such as remote support or upgrading from employees home or from partners, desire to get data/statistics

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2SANY project: http://www.opengeospatial.org/ogc/regions/SANY

3FireEye Annual Threat Report: https://www.fireeye.com/current-threats/annual-threat-report.html
from production. Need a risk assessment when implementing such solutions. Another challenge is that suppliers may have their own links towards their systems. If these stop, then this may even stop the factory.

It is important that fine-grained access to the entire sensor network can be managed centrally by the network owner, so that access can be granted or denied quickly and precisely to specific devices. Certain operations, such as configuration deployment, should also support multi-party authorisation policies for example based on key shares [25], [11]. This reduces the risk that corrupt or radicalised insiders are able to destabilise the factory infrastructure by deploying malicious or faulty system configurations. There will for example be a significant insider threat if laid off employees, or external parties with terminated contract still have access to the system. Another example is that the owner may get sensors installed on the factory premises which communicate with external parties using mobile communications, for example GPRS, where the network owner is not aware of what information the external party is able to extract using these managed sensors. This is a significant concern, since such sensors often are based on generic multi-sensor gateway platforms running traditional operating systems (often Linux) which may be able to communicate using many wireless different protocols in addition to the use the sensor is intended for. This means that a malicious or hacked third party device potentially would be able to compromise internal wireless sensor networks on the production facilities.

C. Security Attacks on an IIoT

According to the Jupiter research 38.5 billion IoT devices will be on the planet by the 2020 [26]. These devices will mainly be smart phones, smart house devices, e-health devices and cars, but there will also several unique devices for specific proposes (e.g. watches, glasses, body analyzers, etc). As the number of the IoT devices proliferate, the challenges for security professionals in the form of attack surface and attack types will increase, perhaps to the level where these problems become unmanageable. With this tendency, the protection of these devices will be an extremely important and difficult task.

The number of cyber-attacks shows a concerning tendency. The number of cyber-attacks is expected to be doubled between 2011 and 2017 [27], [28]. This tendency predicts an even higher growth for IoT devices in the future, because of the huge spread of such devices [29]. Attacks can aim at stealing personal information, gaining money, etc. The attacks are also able to intervene with the normal operation and cause unavailability, annoyance or damage, or they can be used for preparing further synchronized attacks.

The most dangerous attacks are based on zero day vulnerabilities, which are formerly unknown attacks that typically will go undetected by anti-malware software. In this case the window of exposure and overall impact can be extremely high. If an unknown software error appears, then millions of IoT devices can become vulnerable instantly. Several cases has been detected when critical errors were found in crucial software components (web server application, encryption weaknesses, compression software tools etc.) [30], [31]. The problem escalates if the new vulnerability is not patched immediately, so that common exploits appear to take advantage of the vulnerability.

The number of zero day vulnerabilities is expected to be around 700 by the year of 2015 but it also shows increasing tendency [32]. Apart from zero day errors there are other serious threats which are related to configuration errors, improper usage of tools and also to the human factor. The following figure shows the main attack surfaces of an average IoT device.

For any IoT device the following relevant attack surfaces can be mentioned:

- **IoT device operating system**
  - configuration error (e.g. unnecessary services, factory default passwords)
  - software error (e.g. lack of input data validation, memory corruption)
- **IoT device own software**
  - configuration error (e.g. weak authentication method, lack of protection against denial of service)
  - software error (e.g. arbitrary code execution though API)
- **IoT device 3rd party software**
  - configuration error (e.g. lack of encryption, parameter tampering)
  - software error (e.g. file inclusion vulnerability)
- **error in the communication channel**
  - lack of encryption, man in the middle, cryptographic weaknesses
- **vulnerability in the internal network devices**
  - (all kind of web service, database service vulnerabilities)
- **vulnerability in the external individual service provider**
  - (all kind of web service, database service vulnerabilities)
- **vulnerability in the cloud service providers**

As the number of vulnerabilities increases, the purpose of an attack has been extended during the years (stealing personal information, causing annoyance and anger, causing damage, sophisticated spying, cyber terrorism and even cyber war).

The following types of adversary objectives are the most relevant [33]:

- **information leakage** (stealing information e.g. health data, habits)
• stealing money (attacking the bank transfer service of an IoT)
• integrity changing (modifying data for the attacker’s benefit or causing annoyance)
• damaging reputation (attacking successful companies or high traffic service providers)
• availability related: wiping data or blocking operation (causing denial of service can be critical e.g. in the energy sector)
• sophisticated attacks (malware, attacks through command and control servers, etc.)
• cyber terrorism (IoT devices can be connected to critical infrastructures)

A specific IoT device will typically have a specific attack surface. Several IoT related vulnerability was detected and analyzed during the last years. An internet connected gun is analyzed and unauthenticated API and short guessable PIN is detected in 2015 [34]. A vulnerability in the firmware of a network device was revealed which would expose millions of IoT devices to an attack [35]. A baby monitoring device vulnerability can cause lot of annoyance to its users [36], etc.

The attack on the Internet of Things can be more dangerous and can have more critical effects if the targeted computer is an industrial machine. Several virus attack was detected against SCADA systems during the last decade. The Slammer virus [37] targeted Nuclear Power Stations in the USA in 2003, Conficker [38] has several targets including navy systems as well. The first very sophisticated malware that was detected for such purposes was Stuxnet [39]. Stuxnet specifically targeted Programmable Logic Controllers (PLC) of centrifuges for separating nuclear material. Stuxnet was designed to infect modern SCADA systems as well as PLCs. A very similar malware named Duqu [6] was discovered later which aimed to collect information for further Stuxnet like attacks. Stuxnet has several variants, and probably belongs to the same root such as the Secret Twin of Stuxnet [40] or the Flame [41]. There are several cases when a malware is customized to specifically target industrial IoT. A variant of the Havex malware targeted industrial control system and SCADA users in the middle of 2014 [42]. Because malware variants appear very rapidly and can be customized for specific architectures and tasks, it is clear that Industrial IoT hardly differ as a target, but the societal effect of a successful attack can be much higher than attacks on traditional consumer-oriented IoT devices.

V. RELEVANT INDUSTRY CASES

Our main focus has been the process industry and technologies around integrated operations in oil and gas. As mentioned initially in this paper, the process industry is one of the industries for which the concepts of Industry 4.0 will be very relevant. In our survey where we interviewed managers and persons in charge of cyber security, IoTs were one of their main concerns. Manufacturers of equipment and third party service providers wanted to have access to their equipment and sensors or IoT devices, which were internal to the plant’s network. They see IoT as beneficial to both cost and quality, but struggles to have a security strategy which incorporates this new paradigm.

Information sharing was not the biggest concern, as data from IoT devices often were specific for the equipment and revealed little secret information about the manufacturing process. However, if increasingly more devices are installed, then external parties will get a better understanding of the industrial processes which is not acceptable. Data sharing was performed by using traditional methods like VPN with username and password as credentials, firewall routing and role based access control. It could be initiated by the external party after the initial registration and configuration processes were finished. Data quality is a concern, but this will be discussed in our use case for the oil and gas industry. Lastly, security of the IoT device itself with resistance to attacks and hostility was a challenge as hacking could have both a high cost and be a threat to personnel safety.

There are also other stakeholders who may interact with the industry, such as environmental authorities and health and safety authorities. These did traditionally take manual samples, but are now starting to use sensor network for real-time sampling either within or outside the industry premises in order to perform continuous monitoring of emissions or work environment. This is useful, and such continuous monitoring can even be used by the company to optimise industrial processes. There will however be privacy and confidentiality issues with too fine-grained monitoring of such data. Information about problems in production processes could for example affect the market value of the company. This means that data access also for public authorities will also require fine-grained access control as well as pre-processing (for example averaging data) of the sensor data to avoid leaking detailed sensitive information that can be used for example to infer how production processes work.

Our survey for the oil and gas industry focused on equipment manufacturers which wanted to monitor their equipment when used by oil rigs, mostly for the drilling operation. This monitoring is part of a condition based maintenance service. In this case, secrecy of data was a huge problem for information sharing. The rig operator did not want to share operations data with the equipment manufacturer, but the equipment monitoring would reveal many parameters relevant to the operations as the equipment manufacturer often delivered a complete drilling package and monitored most equipment usage. The equipment manufacturer on their side, would not let outsiders access to the monitoring data as this revealed know-how about the equipment. These challenges was not related only to IoT, but IoT can be said to be part of the scenario as monitoring sensors get more advanced.

Availability was another challenge. Stable Internet connections with good bandwidth could not be expected as drilling operations take place all over the world, e.g. on ships where satellite is the only means for communication.

Data quality was mostly a concern with regards to tampering, where tampering could lead to false information. False information could lead to wrong decisions, and as the cost rates for drilling are very high, wrong decisions could have a high cost. Tampering was also a concern for rig operators, as using IoT devices as a backdoor into the control system could have fatal consequences for personnel and environment safety.
and cost.

Despite all the challenges, the oil and gas industries are rapidly moving towards the concept of Integrated Operations, where information sharing and making decisions based on sensor data will have a big role.

VI. Roadmap

This section describe a roadmap for how secure information sharing can be achieved in the industrial internet of things. A problem when performing large-scale deployment of IIoT devices is that there are standardisation efforts going on, however there is still a lack of mature standard that have significant industrial adoption. There are several reasons for this, for example that what constitutes a thing varies widely from very simple purposed-build networked devices to embedded devices running embedded or standard open source or commercial operating systems. These devices have widely different capabilities, which also affects what kind of services they can run to protect their network environment and communication. Another challenge is that regulators need to start focusing on the issue of insecure IIoT, and require regulations and contracts for a certain minimum security standard for IIoT devices. In parallel with this, there are big players such as ARM, Intel and Google who have their own IoT device platforms as well as cloud providers having their proprietary cloud interfaces for these devices.

The next subsection describes one candidate IETF standard for securing Internet-based IoT devices. Research, standardisation and industry adoption by IIoT device vendors is probably the first step towards increased security in IIoT. In parallel with this can existing organisation already now use existing good practices for securing IIoT networks in the short run. There are also some research initiatives that aim at industrialising security solutions built around existing vulnerable IIoT devices and SCADA systems using techniques such as software-defined security. In the long run, standardised security solutions based on existing industry standards for process control such as OPC-UA that could consolidate the IIoT devices within the manufacturing plant in a secure way with fine-grained access control.

A. Security Considerations in the IP-based Internet of Things

The Internet Engineering Task Force (IETF) has a work in progress draft covering security considerations for IP-based IoT [43]. The draft examines the current state of the art, further possibilities, and challenges in the security realm of IoT.

An IoT device is referred to as a thing whose life cycle starts during its manufacturing, and ends when it has been decommissioned by its user. During the end of the manufacturing cycle, the thing has an initial bootstrapping where it securely joins the IoT network at its location. This also covers the initial authentication, authorisation and configuration of necessary parameters for trusted operations in the network. When the device is connected to the IoT network it is considered operational until it needs maintenance, for example installing a software update which is followed by a re-bootstrapping of said device. This continues until the device is no longer in use and has been decommissioned.

The life cycle presented is used as a base for identifying where possible threats could happen. The threat analysis covers the following protocols: HTTPS, 6LoWPAN, ANCP, DNS, SIP, IPv6, ND, and PANA. There are several groups of threats considered which either compromises the thing itself or the network as a whole: cloning, malicious substitution, eavesdropping, man-in-the-middle, firmware replacement, extraction of security parameters, routing attacks including sinkhole, black hole, privacy threats, and Denial of Service. There is also a risk that things can be cloned and sold for a cheaper price in the market by competitors. Untrusted manufacturers could also change the functionality of cloned devices for example by adding a backdoor. Related to the cloning is malicious substitution where one thing can be swapped with another “copy” of lower quality, which could lead to degraded functionality. Eavesdropping attacks could happen during bootstrapping events before any secure communication has been established, which can compromise the authenticity and confidentiality of the communication channel. This phase may also be vulnerable to man in the middle attacks. Firmware replacement attacks can happen during a maintenance phase, where an attacker can exploit the fact that the device is under update and install malicious firmware.

This draft standard presents the current state of art (2013), where protocols such as ZigBee, BACNet, and DALI play the key roles, but the trend is moving towards all-IP solutions. One of these solutions is the 6LoWPAN working groups which focuses on transportation of IPv6 packets over IEEE 802.15.4 networks. For IP-based solutions there is a plurality of security solutions to consider, and the draft identifies and examines the following: IKEv2/IPsec, TLS/SSL, DTLS, HIP, PANA, and EAP. One of the problems identified when using an IP based security solution for IoT is that there are minor differences between IoT protocols and regular Internet protocols. This could hamper end-to-end security if communication relies on protocol translators between sender and receiver.

Five security profiles are defined in the draft standard ranging from IoT devices with no security needs, home usage, managed home usage, industrial usage, and advanced industrial usage. The industrial security profile is where operation on devices relies on a central device for security, while advanced IIoT can also enable ad-hoc operations between themselves or they can have more then one central control device. Both of these profiles can have a network manager located in a 6LoWPAN/CoAP network, which also handles the key management. Under industrial usage, devices are required to be associated with the network in a secure way the first time they are introduced. Broadcast messaging should be secured with entity authentication (ID-CoAPMulticast). Remote management is done through a backend manager which is in charge of managing the different software installed or information exchanged within the network.

The draft identifies that a basic building block when considering the next step towards a flexible and secure IoT for networks would be DTLS, One promising implementation towards embedded development is TinyDTLS which offers
an open source implementation of the protocol usable for resource constrained devices. Good solutions for bootstrapping is still lacking, since there is a real need for good protocols that resolves the initial authentication, authorisation and configuration. Secure resource discovery security issues is still unclear, for example on how to handle secure DNS and time synchronisation. Some vendors have proposed proprietary extensions to handle this, such as the SmartAMM protocol developed by Develco systems. The way security is layered where each layer take care of its own need, might not be so feasible for a small device where resources are tight. The draft argues that there should be more inter-connectivity across these layers to be efficient and manage the whole security from link to application instead of having multiple managers.

B. Short-term Solution

There are some basic principles that should be kept during the protection of IIoT. To prevent and detect any malicious activity in the short term, the following steps are recommended to be followed. The objective of the short-term solution is that a vulnerable infrastructure can be protected using a surrounding set of security tools based on existing good practices such as firewalls, intrusion detection system, vulnerability scanners etc. The PRECYSE security methodology, tools and architecture is an example of solution based on existing and some new security components that supports adding protection to a vulnerable critical infrastructure this way. The PRECYSE project did for example demonstrate adding protection of SCADA telecontrol systems in the energy sector, as well as vulnerable city traffic controllers [In press]. The PRECYSE architecture uses the concept of configurable security Domains and Enclaves, where each Domain enforces a given security policy for a given Enclave.

Other good practices that can be applied in the short run are:

1) Network Segregation: One approach that has been proposed for enforcing network segregation, is adding surrounding security tools which effectively are able to segregate and monitor the networks in order to provide higher security awareness with identification of policy violations. The objective then adding software-defined security solutions for segregating the network, as well as monitoring the resulting network Domains and Enclaves.

2) Continuous Monitoring and Analysis: Computer systems have become more and more complex which makes the protection much more difficult. Due to the continuous rapid development of sophisticated attacks and the previously known and unknown threats and attack vectors, the most secure solution is to continuously analyse the system behaviors and data. All computer system can be analysed in several different ways.

3) Log Analysis: Most of all computer device and software such as network devices, operating systems, applications and all manner of intelligent or programmable devices document their activity by producing logs. Logs can be used for auditing, or checking the compliance according to regulations or trouble shooting. Logs are also good for forensic activities and detecting intrusion attempts. Several attack types can be easily recognized by log analysis such as attacks producing large amount of log entries (e.g. brute forcing). Other types that have a definite attack pattern can be detected easily as well. Host-based intrusion detection systems typically support such log analysis.

4) File Integrity Monitoring: File integrity analysis is mainly for operating systems and software for validating its integrity with some verification method. The most frequently used verification method is the calculation of some kind of cryptographic checksum (hash) which can be compared to a base value or a list. Checksum verification can be used for identifying harmful files (black listing) or it can be used for identifying allowed files (white listings). The latter is obviously stricter and more secure however from the point of view of functionality black listing is easier to implement. Host based intrusion detection systems typically also support file integrity monitoring.

5) Network Traffic Analysis: Network monitoring or network traffic analysis is needed for detecting malicious activity by analyzing the network packets. Intrusion or malicious activity recognition can be based on patterns or behavior analysis. However sophisticated malware can hide the information in covert channels, which can be so subtle that only pixels are changed in a legitimate picture. In that case, network traffic analysis can only detect the suspicious destination of the packet or the amount of network packets that are sent to the destination (e.g. command and control server).

6) Memory Dump Analysis: Memory dump analysis is one of the best way of detecting unknown and well known malware and malicious activity in the operating systems memory. Volatility framework is able to analyse several type of memory dumps using advanced techniques. Hidden processes as well as libraries loaded for malicious activity can be detected, which facilitates the detection of sophisticated intrusions into the system.

7) Regular Malicious Activity Detecting Tools: In addition to specific memory, network traffic and file analysis, the usage of regular Anti-Virus (AV) and security products with up-to-date attack pattern database and heuristic search methods is a must.

8) Continuous Updating and Patching: Continuous updating of the system and software (especially the 3rd party software) is crucial from the security point of view. Unknown software errors can provide the possibility of arbitrary code execution on the operating system for the attacker. In "lucky" cases a software error only leads to denial of service, which in itself can have drastic effects on a critical infrastructures, since availability typically is of paramount importance. Malicious attacks may be even worse, since they may compromise the device without being detected, and can be used as a bridgehead for further attacks into the critical infrastructure as well as for industry espionage. It is important to monitor security news.

\[\text{SmartAMM: } \text{https://stateofgreen.com/en/profiles/developproducts/solutions/smartamm-makes-it-easier-to-monitor-private-households-electrical-appliances}\]

\[\text{The Volatility framework: } \text{http://www.volatilityfoundation.org/}\]
sources and react on knowledge about new vulnerabilities as quickly as possible.

9) Regular Vulnerability Testing: The security of a system is to a large extent determined by the design of the system. Continuous monitoring should be used to detect any malicious attempt, and vulnerability testing can draw the attention to unknown errors. The vulnerability test can be related to the whole system, or a specific component (e.g. software vulnerability test, penetration test of a specific computer through the network, etc.)

Vulnerability testing should be done at regular intervals since a new analysis can reveal new threats.

Vulnerability test can be done in terms of:

- Black box (the attacker has no access to the system and no previous knowledge)
- Grey box (the attacker is a user of the system with restrictions)
- White box (the attacker has a good overview of the system, e.g. administrative rights)

10) Proxy solutions: Using proxy solutions to build protection around legacy or vulnerable solutions is a well-known technique for increasing the security. This type of solutions can implement access control functionality, limit the commands that can be sent to the protected device or network, perform inspection and filtering, etc. In cases where a sub-set of data should be made available for e.g. a supplier, the relevant data can be exported to a DMZ using a trusted process, and thereby effectively remove the need for giving the supplier access to the sensitive network. If needed this trusted process can also implement functionality to reduce the detail level of the exported data.

C. Long-term Solution

This section outlines possible long-term solutions for improving the security of IoT devices and facilitating necessary data access. It is assumed that the long-term solution will include developing a security gateway based on existing industry standards such as for example OPC-UA. This would allow for integrating various IoT devices and expose them to external services according to a strict definition of need. Significant research and development as well as standardisation and industry adoption of these standards is however required before such a solution will be successful.

1) OPC-UA Managed Gateway for Controlled Information Access: The web service mapping of OPC-UA supports the WS-Security standard, and the native mapping maps these to similar cryptographic primitives. OPC-UA supports its own service discovery, as well as using standard service repositories such as LDAP or UDDI [2]. OPC-UA defines objects in terms of variables, methods and events. This object model is mapped to the address space as nodes which are interconnected by references. OPC-UA allows for connecting to existing OPC solutions using OPC UA wrappers and proxies [2]. Another method is utilising OPC-UA gateways and adapters.

An OPC UA wrapper is able to seamlessly integrate an OPC COM server [2]. The wrapper is responsible for handling endpoints and managing UA encoding/decoding, security, transport and mapping the COM server’s address space to UA [2]. Data change call-backs initiated by the COM server are returned as OPC UA Publish requests.

An OPC UA proxy allows for conversion in the other direction, so that OPC COM clients can communicate with an OPC UA server [2]. A problem with mapping using OPC UA proxies and wrappers is that it is not able to map new concepts and technologies to old COM implementations [2]. Specifically, different profiles will be needed for mapping the OPC Data Access (DA), Alarms and Events (AE) and Historical Data Access (HDA) specifications to OPC UA, since these standards have different semantics. Also, previous OPC specifications did not address security, which means that functionality for managing confidentiality, integrity and application authentication must be added on the OPC-UA side. Also, performance, difference in transmission rate and latencies can be an issue with such protocol conversion, depending on the real-time requirements of the use case.

An OPC UA gateway is one possible solution for solving these issues by integrating the different wrapping components, as well as adding the necessary security functionality. The strong inner security model of OPC UA facilitates hiding security sensitive processes from malicious attacks, whilst still providing the necessary functionality for accessing the underlying vulnerable COM-based infrastructure. Figure 2 illustrates at a high level how an OPC-UA gateway can be extended to support a service authorisation layer providing fine-grained access to underlying OPC-UA services based on an authorisation and privacy policy. The gateway supports handling and converting messages between OPC UA as well as the traditional COM-based infrastructure supporting both OPC DA, A&E and the HDA interfaces via the UA services API. The gateway concept allows for supporting adapter plug-in modules for adding new functionality that by default is not supported by the standard conversion profiles.

VII. RELATED WORK

As the number of IoT devices proliferate, several research initiatives focus on finding a general solution for the security of the IoT. Ukil at al. proposed a solution for embedded security where the hardware and its data aims to be secured [47]. Also a general solution is proposed by Cisco Security [48]. This is a framework that may be used in protocol and product development as well as in policy enforcement in operational environments.

In case of Industrial IoT, previous research mainly addresses threats of IIoT. Sadeghi at al. gives an introduction to Industrial IoT systems, the related security and privacy challenges, and an outlook on possible solutions towards a holistic security framework for Industrial IoT systems [49]. Xu at al. summarises the current state-of-the-art in industrial systematically [50]. Meltzer discusses security aspects of the Industrial Internet of Things due to the explosion of IP-connected devices used in such areas as control systems, manufacturing, utilities, and transportation [51]. Other studies focus on specific
problems of IIoT such as the vulnerabilities and risks in the industrial usage of wireless communication. NSA provided a framework description for Assessing and Improving the Security Posture of Industrial Control Systems.

VIII. SUMMARY

This article has proposed a roadmap for handling the problem of secure information sharing with external vendors in an IIoT. It proposes how IIoT should be secured both in the short term by applying existing good practices in a structured manner, as well as utilising and extending security toolsets such as the PRECYSE architecture for protecting vulnerable IIoT devices. In the long term we envisage that better solutions will be needed, for example for an OPC-UA gateway with support for very fine-grained access control to data in IIoT devices. This should be integrated with the organisation’s own single-sign-on authentication infrastructure, essentially providing the possibility for assigning or revoking access to individual IIoT devices as well as providing or denying access to certain data (individual XML elements or attributes) within messages from these devices.

IX. FUTURE WORK

Future work involves research on integrated solutions for protecting vulnerable IIoT devices, for example by building software-defined security solutions on top of existing frameworks such as the PRECYSE architecture. Long-term research could involve implementing an OPC-UA gateway with support for firewall functionality as well as very fine-grained access control, for example based on the Reversible Anonymiser, which would allow for policy-controlled access to individual data in the OPC-UA messages.

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