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Reliability Solutions for a Smart Digital Factory using: (1)RFID based CEP (2)Image Processing based Error Detection (3)RFID based HCI

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Abstract

New technologies have a great influence on the production process in modern factories. Introducing new techniques and methods is crucial to optimize and enhance the working of factories. However, ensuring a reliable and correct integration requires complete evaluation and assessment. In this thesis I utilize RFID systems and image processing to develop and implement real time solutions to enhance and optimize the production and assembly processes. Solutions include: RFID based CEP to detect production error, image processing based errors detection to detect post-assembly errors, and RFID based HCI to help workers in assembling products. Errors that are detected using RFID are: sequence errors, synchronization errors, pre-assembly order errors, part-product mismatch error, and missing parts errors. Errors that are detected using image processing are: incorrect part position errors and missing parts errors. RFID based HCI consists of a tool to help workers at assembly points to correctly assemble parts to their products using visual instruction. I have constructed prototypes for all the solutions. As well, I have deployed them in the Lernfabrik(learning factory) which is a real manufacturing environment for practising the production and assembly processes for trainees and students. Under the optimal settings of the RFID readers and tags, the system detects all types of errors reliably in real time. The image processing algorithm detects errors with 100% accuracy in real and normal lighting conditions of the Lernfabrik.

Acknowledgment

I would like to thank my supervisor Bilal Hameed for his help, motivation, encouragement and guidance throughout my working on this thesis.

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Chapter 1

Introduction

Factories are an important factor for the growth and development of counties, as well as an engine and a driving force of their economy. They are the heart of industry. The technology of manufacturing has evolved through many improvements and enhancements for the last 100 years. Back then, when Henry Ford developed the first assembly line[1], workers used their hands to follow up with the products parts and to ensure correct assembly and products flow. Recent advancements of technology made factories evolve progressively through introducing more and more innovative tools and ideas. Computer and communication technologies have greatly influenced the structure and the organization of factories and the process of manufacturing. Companies have used technologies to automate assembly lines, to control and to monitor products while moving on them.

In recent years auto identification (Auto-ID) systems have been gaining lots of attention from various application domains such as security, industry, sports, transportation, education, and manufacturing. Examples of Auto-ID systems include voice identification, finger procedure, optical character recognition barcode systems and RFID Systems. A radio frquency identification (RFID) wireless system is a powerful tool to detect the presence or absence of objects and to know their relative positions. It comprises two main components: (1) a transponder (tag) (2) an interrogator (reader). To make an object identifiable, a tag is attached to it. Tags are of two types: passive and active. A passive tag does not need a power source. It uses a coupling element to obtain power from the reader.

An active tag has its own voltage supply (a battery) and gets power from it. A tag contains also an electronic microchip that is used for processing and storage. A reader reads identification data from tags and it could act as a writer and writes data to them. Utilization of RFID systems has great benefits for improving the manufacturing process in factories. Figure 1.1 shows the growth of RFID systems for possible auto-id applications. [2]

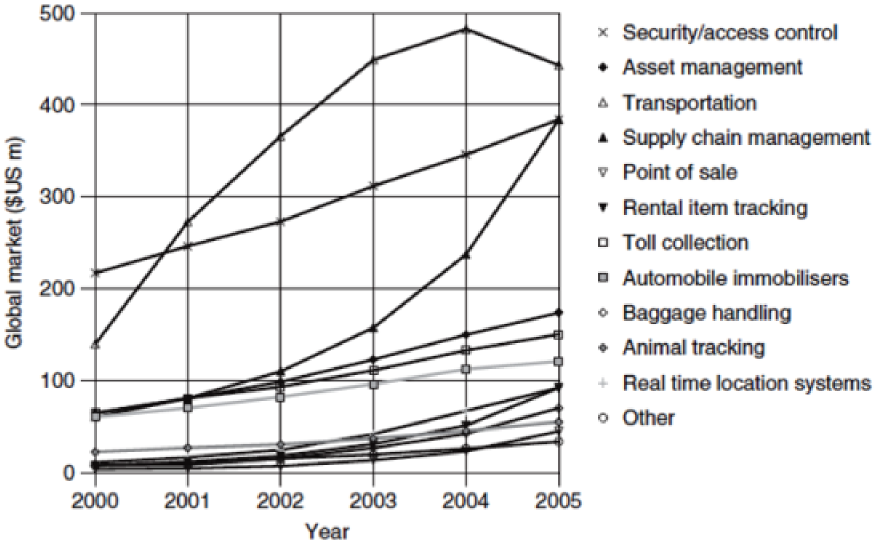


Figure 1.1: The estimated growth of the global market for RFID systems between 2000 and 2005 in million $US, classified by application[2]

With the increased competition among companies and the eagerness to attract more customers modern factories have been producing more and more custom-made products. Build-to-order production gives customers the opportunity to tailor products as they wish. Building products according to customer's preferences increases the competence between manufacturers but make customers happier because they get what they exactly want. Several manufacturers have adopted build-to-order production style. Examples include automotive companies such as BMW, Porsche, and Mercedes, as well as computer companies such as HP, dell, and IBM, e.g., if you want to buy a PC from Dell you can use the online portal to build up your PC according to your preferences. Porsche offers its customers 10^7 variants [3]. But they have to wait a three months lead time before the car is ready. During that period, the company does production planning and management. In order to ensure correct, optimized, and error free assembly process, Porsche is using a set of error prevention techniques during: (1) the planning process and (2) the assembly process. During the planning phase similar and closely related cars are arranged together, therefore the high variety becomes more ordered and disciplined. This simplifies the assembly processes, workers will have to do a common thing for a series of semi-assembled cars instead of doing a different thing for every single car. During the assembly process they utilize barcode and lighting systems to prevent assembly errors. At an assembly point, incoming semi-assembled vehicles come forward for assembly. A barcode tag is attached to each of them. Vehicle parts are arranged on shelves (or come in through conveyor belts). Every shelf has a light pulp next to it. A worker uses a barcode reader to read the tag. According to the assembly plan one of the lights goes on or blinks for a period of time indicating that the semi-assembled vehicle should be assembled using a part from the corresponding shelf. These techniques aims at preventing an error from happening, Porsche is using also techniques to discover errors within a maximum of five minutes after an assembly procedure. At certain assembly points there are carts that are filled with assembly parts. Every five minutes a cart should become empty and i.e. all items inside it should be consumed. In case a cart is not empty after five minutes, items in it were not consumed, i.e., there were assembly errors in the last five minutes at the corresponding assembly point.

Even with the utilization with technologies such as barcode, workers get physically and mentally stressed due to the nature of repetitive tasks. Moreover, owing to the huge variety of products it becomes difficult to ensure an error free production process. Various errors emerge during assembling parts to its products, such as sequence error, i.e., product parts are moving on the assembly line in the wrong order; synchronization error, i.e., parts reaching the assembly point belong to a different product other than the one available in it; assembly order error, i.e., parts of a specific product reach the assembly point in the wrong order. Moreover, the large number of variants makes managing the state of the product really tough. Also, a worker might forget to scan the product part, or he might forget to press the button to indicate the completion of

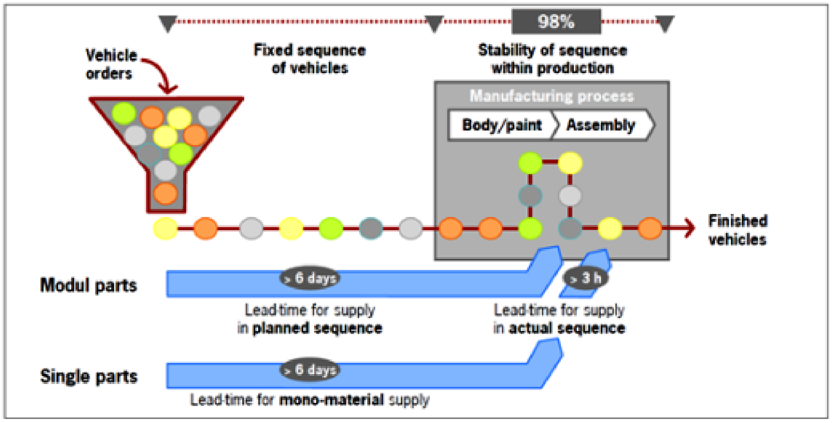


Figure 1.2: Porche production system[3]

assembling a specific part.

Real-time monitoring of assembly lines and providing guidance to workers during the assembly process are crucial to help addressing these problems. Many technologies and techniques have been used for this purpose. Barcode and video processing are examples of such technologies. Pick-up-lights and visual instructions are examples of such techniques. Companies have been using barcode extensively owing to low cost and its high reliability in monitoring. But it has some limitations: barcode readers should be very close to the item to read its label; the label should be in sight of the reader for the reading to work; and it is not possible for the reader to read multiple labels at a time. RFID wireless technology is a promising substitution for barcode. Attaching an RFID tag to each part makes it possible to follow up with all parts that are moving along the production line. And making the right decision about the distribution of readers utilizes and optimizes the reliability of the RFID network. Employing RFID in a production environment has a great benefit when used for the monitoring, control and guidance of build-to-order products. RFID has attractive features for such a job: it needs no line of sight between the reader and tags; a reader can read multiple tags at a time; reading from a distance is possible; tags are becoming cheaper day after day; readers can have interfaces to higher level processing devices, such as a PC. However, RFID has short comings; its operation comes to be less reliable in harsh environments such as settings with lots of metal in the surroundings. Moreover, readers become untrustworthy if they are to read a large number of tags at the same time, they might also have wrong readings. Current applications of RFID systems in manufacturing are limited to the level of the tracking of product's frame, e.g., car chassis or computer case. Ford has been using an RFID system to track auto and truck frames throughout the different assembly and painting phases. They used a 23-digit serial number stored in RFID tags that are attached to every frame[5]. The tag tells the worker about what should be done to the vehicle at every production stage. Also it indicates the remaining activities that should be further done to the car. However, applications of item-level (not whole product) tracking and monitoring are still under research. Tagging each component of the product increases the visibility of the production. And makes it more efficient to tracking product parts and monitor them. Also it ensures a robust and reliable assembly because each assembly step would be visible within the system. And in case an assembly error occurs it will be detected very soon. But tagging every single component of the product would generate immense number of RFID data that need to be filtered and processed to deliver high level events that are useful for the worker and the manufacturer. Generally, Complex Event Processing (CEP) handles a set of atomic events to generate complex events, such as aggregation, composition, containment, sequence detection, location determination, and path tracking. Complex event processing is a tedious and difficult task. Therefore different software companies built CEP platforms to simplify and utilize system resources for better CEP process. Esper [4] is a complex event processing platform. It supports CEP by means of an optimized language to discover patterns and meaningful composite events from a stream of primitive events.

In this thesis I develop and implement RFID and image processing based solutions to optimize the production process through employing RFID readers to discover pre-assembly errors so that assembly errors are avoided. And to discover assembly errors in case they occur using both RFID readers and image processing. I also, implement functions to give the worker in the assembly point visual assembly instructions based on incoming products. RFID based error detection utilizes a CEP engine (Esper) to find error pattern from the stream of RFID events. Errors to be detected are: sequence errors, synchronization errors, pre-assembly order errors, missing part errors, and part-product mismatch errors. The image processing solution is to detect incorrect position errors and missing part errors, by identifying the position of each part of the product and discover any placement errors.

Thesis organization In chapter two I will discuss the related work to this thesis. In chapter three I will introduce the system architecture. In chapters four, five and six I will discuss the three developed solutions. Chapter seven contains the evaluations and finally chapter eight is the conclusion.

Chapter 2

Related work

2.1 RFID applications in manufacturing

2.1.1 RFID sensor network based object tracking

In [6] Wang, et al. developed an RFID based object tracking system to automate assembly lines. They followed a grid based approach where RFID readers are spread over the factory as a grid at defined positions Figure 2.1. The main objective is to predict the location of an object to improve the efficiency of assembly line operations. They used a convex based range free tracking algorithm [7]. When several RFID readers read a certain tag attached to moving object, its position is within the intersection of the ranges of the readers. The system only indicates the predicted location of moving objects throughout the assembly lines.

Comments: The paper constructs a solution to track RFID tagged objects moving within a certain geographical area. The technique allows knowing the relative location of objects. the paper does not suggest any solutions to avoid or detect assembly errors in a factory.

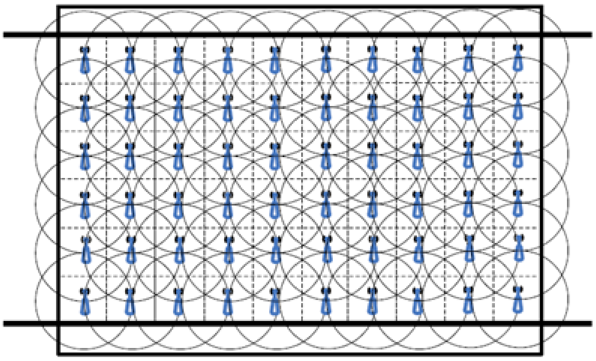


Figure 2.1: Tracking system in assembly line[6]

2.1.2 RFID based concurrent intelligent manufacturing

The work in [8] discusses the benefits of combining concurrent intelligent control with RFID technology in manufacturing. It discusses how the integration of RFID with the concurrent manufacturing model can enhance the productivity. In the production process, both design and manufacturing run concurrently. A customer (who acts as the designer) indicates the specifications of a product and an RFID tag is assigned this information according to his requirements. If he, however, makes changes to them; the new specifications are updated on the tag. In the middle of the manufacturing process, parts will be treated accordingly to the updated state of the tag.

Comments: The paper discuss possibilities of engaging the customer into the production of products and how RFID technology can be utilized for that. However, the paper does not suggest any solutions to detection or avoid errors.

2.1.3 RFID based sorting and stacking

In [9] the authors built an RFID based stacking-transport system. The system was applied on a Tobacco production line Figure 2.2. A high frequency RFID tag was attached to each cigarette box. And it contained information about its brand. A high frequency reader reads tags on coming boxes and sends the brand information to a sorting controller which in turn determines where to route the box. A stacker crane robot stacks forwarded boxes on pallets according to their brand. Pallets also have RFID tags. At the end of the assembly line another reader that uses another frequency updates the tag of each pallet, which is now full with boxes, with the new information about the contained boxes. The paper compares the system to the existing barcode based systems. The former enhances time management and reduces the number of damaged products because it needs no manual scanning of tags. Also, the memory property allows better management of the products in the warehouse.

Comments: The paper presents a manufacturing application that was developed based on RFID system. No error detection or avoidance techniques were suggested.

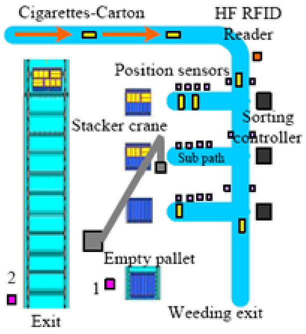


Figure 2.2: Scene in cigarettes production line[9]

2.1.4 RFID enabled aerospace manufacturing

In [10] the authors present a theoretical model and a generic RFID framework to build an RFID-enabled aerospace manufacturing. Their work is a step towards filling the gap between the physical flow of object in the aerospace manufacturing and their planning in the virtual world. In their paper, they discuss various issues and matters. Next I will briefly discuss each issue. *Regularity requirements:* in aerospace manufacturing, parts should comply with certain safety rules and quality standards such as the FFA Federal aviation administration standards. *Quality assurance and control:* monitoring the manufacturing processes with RFID enables recording and knowing various problems. Future operations are modified, corrected and optimized based on previous quality issues. In addition, Quality attributes can be written directly to the RFID tag. *Production planning and control:* in planning the amount of needed materials and parts as well as the required capacity of workers is decided. Well established identification of parts using RFID enables tags with large size of memory to store the identification data. *Product traceability:* for aerospace manufacturing it is very important to track down all parts in every phase and level of the production. Starting from inventory till the machines are ready, it is necessary to recognize where exactly the part is. *Inventory visibility:* RFID technology makes inventory management and control simpler, easier and more effective. With the huge volume of material and parts in the inventory RFID is a solution to know what and what is not on the shelves. *Labor productivity:* managers can ensure effective production by tracking workers throughout the working hours. Also it is possible to send alarms in case a worker is about to go into dangerous places. In their paper, they present the following theoretical models and simulation:

- *RFID network architecture:* readers are positioned along the production line collecting data from the tags and send them information in case of a change. Information about the production flow is stored on the tags. In case the production plan has changed readers write the new data into the tags so that they have the newly updated information about the production of the parts.

- *RFID readers/tags configuration:* locations of readers have to be evaluated in order to get the highest optimization for feasibility and readability. Tags also have to be configured properly and placed in such a way that result with best readability and the least interference.

- *Identification of defective products:* production wastes results when defective parts continue in the production flow without being discovered. RFID can see and detect defective parts as soon as they appear.

Comments: The paper presents general ideas and models to enable RFID based aerospace manufacturing. However, it did not develop any practical implementations.

2.1.5 RAMS an RFID Activity Monitoring System for discrete manufacturing

In [11] the authors build RAMS (RFID Activity Monitoring System). The system is an application of RFID technology in production control for a discrete manufacturing system. The aim of the system is to have real time monitoring on the production process. The authors applied RAMS to a bathtub production control where bathtubs are produced in two types: normal and special. Each of them has a different production plan. Customers can give their preferences when ordering the special type. Possible problems during production are: missing components, workers moves products to the wrong place or forgets to move them at the right time. Also, managers need to follow up with orders of the special bathtub type. Figure 2.3 shows the data flow within the system. The middleware reads RFID tags from the readers and prepares them for further processing and usage. Data generation module converts tags data from XML into data objects. Data is stored then in a database. The result of using RAMS is an increase of 5% of service level, an annual increase of 1.5% of sales quantity, a reduction of delayed production by 60% and a reduction of inventory cost by 0.5 million USD every year.

Comments: RAMS is limited to updating the state of the products as they go from one production step to another. as well as the timestamp of entering and exiting each step. The system does not do any assembly errors check.

2.1.6 RFID based Moisture-Sensitive-Devices tracking system

In [12] Lathem et al. implemented a tracking system based on RFID. It tracks moisture sensitive devices that are used in man-

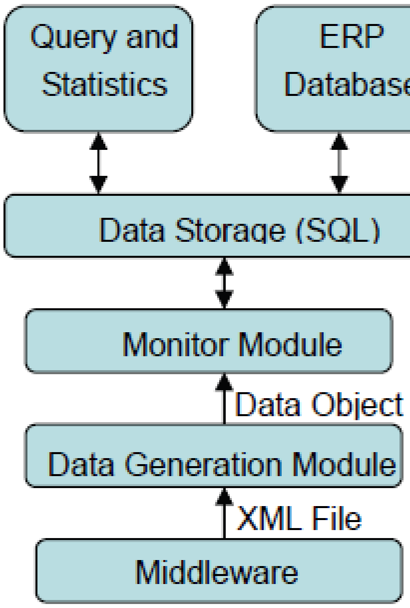


Figure 2.3: Data flow of the system[11]

ufacturing. Manual tracking is inefficient, error prone, and time consuming. Also, resealing, recording and storing of MSDs require two employees working for 90 minutes a day. The system tracks the time period during which trays containing MSDs are exposed to open air. Each tray is attached an RFID tag. When a tray comes in, the system starts logging its exposure time. It gives a warning if the time of exposure is about to reach its limit. The system has three basic components: (1) hardware (2) data storage, and (3) control. The control component moves system data between the hardware and the data component. In addition, it displays information to the use using a GUI. The hardware component scans RFID tags and returns the result to the controller. Data storage is a database containing logs and readings for future assessment. Reader position and signal strength: to have optimum readings from the RFID readers, they should be placed in a way such that all tags within its range is read and outside it are not as well their signal strength should be. In this system, the best position for readers was discovered to be four inches away from the back of the boxes that initially contain the trays. And the optimum signal strength was 20 dBm.

Comments: The system is limited to temporal tracking of MSDs and giving warnings if the air-exposure time is about to elapse. The system is not concerned with detecting assembly errors.

2.1.7 Application of RFID technology in manufacture of household electrical appliance

In [13], Tan presents RFID based applications to address various issues that arise during manufacturing household electrical appliance. Such as: manual data manipulation, materials control and management, organization of production, visualization of production process and notification of defective products very soon. The author designs a system for production management based on RFID. The system provides the following applications and services: employees and product status monitoring, material tracing, quality control, management of products and raw materials, updating the state of products and route them according to RFID tag information. The structure has a centralized management and a decentralized control. Each production line has its own control, whereas all the production lines are under a centralized management.

The main functions within system are: (1) System management: managing system information and setup its configurations. (2) Production operation management: manages the production of products according to the production plan. It also controls the movement of materials on the rails. (3) Production enquiry management: provides the management staff with the statistical data and diagrams showing the state of the production. (4) Resource management: manages the plans for new material and equipment according to the requirements of the incoming orders and their production. (5) Production monitor management: provides updated real- time state of the production process to workers and managers. (6) Data interface: supply factory information systems with data from the system.

Comments: The paper proposes a design of an applications system based on RFID that provides services to support production management. However it does not suggest any assembly errors detection.

2.1.8 RFID consistency framework for production monitoring

In [14] Hameed et al. proposed an RFID based consistency management framework for production monitoring in a smart real-time factory. They argue that the reliability of readers is influenced by the RF interference especially when a reader has multiple tags within its reading range as well as the presence of metal material in the working area. The main contributions of the paper are: (1) probability based sequence detection and (2) a consistency stack. To detect a sequence of RFID tagged objects the framework aimed at utilizing unreliable RFID readers to deduce the correct sequence of items moving on the production line. In this work a production path is designed to abstract the flow of production items on assembly lines. The production path is divided into reading areas. Sets of RFID physical readers (PR) are placed in each area. Each set is responsible for detecting tagged objects within their respective reading area. It is also connected to a virtual reader (VR - e.g., a pc) that is gathering data from PRs and represents an abstraction of them that hides their flaws. Along the production path, each VR sends data to the next virtual reader on the path and accepts data from previous one. A consistency repository has a complete view of the whole system, i.e. the factory layout, production paths, and locations of VRs and PRs. The accuracy of PRs was measured according the average number of tags that they can detect out of the overall number of tag located within the discovery range. Detection of sequence is based on the partial sequence detection of objects which is then combined with other partial sequences to identify the final determined sequence. Within the consistency stack Figure 2.4, they distribute the consistency issues over five layers. It includes: synchronization consistency, sequential consistency, missed reading detection, false reading elimination and duplicates elimination. The first two are contained within a production consistency sub-stack and the others in an RFID consistency sub-stack.

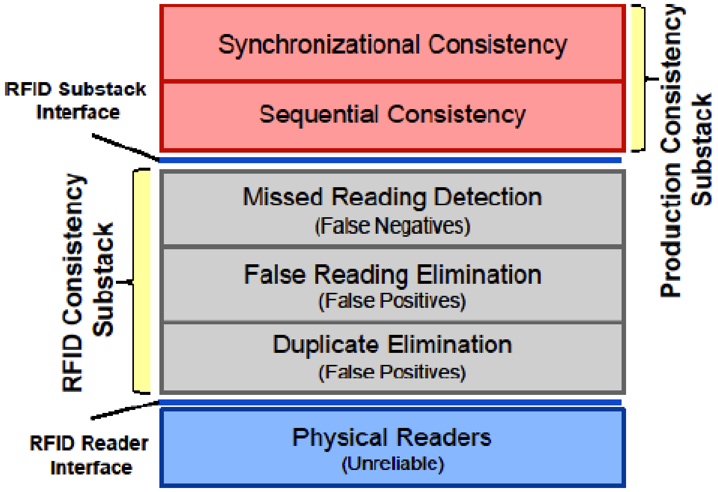


Figure 2.4: Consistency Stack for RFID Deployments in Production Environments [14]

The probability based sequence detection was simulated using P2P platform[27] . The results were that the accuracy of detecting a sequence increases when the detection accuracy of physical readers is increased and the number of tags in their range is reduced.

Comments: In this thesis I extend the consistency stack that was developed in [14]. I will discuss the extension in chapter four. The paper propose an algorithm to conclude a sequence of objects using a partial sequence. However, this thesis provides several solutions that covers pre and post assembly errors and its not limited to sequence errors detection.

2.1.9 The smart factory as a product service system

In [15], Hameed et al. envision the smart real time factory as a product service system. The paper discusses the possible informational services that a smart factory can offer to customers. The paper discusses in details some of them. I will briefly cover the main point of three main services. (1) Production tracking for consumers: in a smart factory consumers should be able to have a real time progress reports on their ordered products. At any moment a product should have its state updated according to its location and assembly progress. Hence, a consumer can have full insights over his order. (2) Dynamic product reconfigurations: customers might want to change the configurations of their order while it is being manufactured. Dynamic reconfigurations offer consumers and producers the power to follow up with products and reconfigure them on the fly. (3) Production data traceability for producers: tracing the production state and the products flow is essential for managers to enhance the process in the future and to ensure higher quality attributes.

Comments: This paper is about making the product components visible during production, which means attaching RFID tags to each component. In this thesis I apply and evaluate item-level tagging to detect assembly errors.

2.1.10 More applications of RFID in manufacturing:

In [16] the authors present a detailed discussion on applications of RFID in manufacturing. Major applications include warehouse management, manufacturing engineering, and mistake-proofing of mixed-flow assembly which is considered as a Poka-yoke technique. Poka-yoke techniques targets detecting defects in products. It aims at discovering mistakes (and correct them) as early as possible. They also review a number of internal needs driven application, such as: Toyota's vehicle tracking throughout the manufacturing process as well as during its lifetime after production. Process automation at Harley Davidson, where an RFID tag is attached to each bin, so that when a bin reaches a certain area the responsible worker obtains the necessary information and instructions on what to do with the bin. Tracking vehicle's seat throughout the assembly process in Johnson Controls. Beer keg tracking at TrenStar. Denim attire tracking at GAP to improve customer service. In [17] the authors inspect the applications of RFID in manufacturing and explore their perceived benefits in the field. They made several case studies:

- Production Activity Control (PAC) at Club Car at Augusta, Georgia manufacturing plant. They integrated an RFID system to their manufacturing system. In their system vehicles are carried using carriages moving on the assembly line. RFID tags are attached to each carriage containing an ID. When a vehicle reaches an assembly point an RFID reader senses its value and acquire from a database the required processes tools and activities that should be used on the vehicle.
- Inventory management at Viper Motorcycle Minneapolis, Minnesota. They used active RFID tags to track parts and subassemblies such as: tires, headlights, gas tanks. in addition to labor. They used the tracking information to have details on the available resources and determine how much is required. Dealers of the company can access the tracking information available from the RFID system to show customers the progress of their under-assembly motorcycles.
- Quality control at Colder Products Company such as quick-release couplings and tube fittings. They embedded RFID tags inside the male part of the coupling that is used for with liquid packages. The tag contains information about the type of the liquid that should be used with the coupling. In case the coupling is not compatible with the liquid the system gives an alarm.
- Plant maintenance in an oil refinery: California oil refinery used RFID tags to track pressure relief valves (PRV). During maintenance, all PRVs are moved for inspection and repair. Because PRVs look similar, few of the valves are sent to the wrong location for inspection. To solve this problem they used RFID tags including information about their location. This eliminates the confusion about the location of the valves, and ensures transportation of PRVs to their proper location.
- Developing a new product at IBM: the production of 300 mm silicon wafers at IBM increased the value of errors in manufacturing. More than 600 processes are applied to the wafers and this requires precise and controlled routing and rerouting of wafer batches. IBM used passive RFID tags to track and identify batches. Utilizing RFID eliminated human errors and

> made it easy to monitor the production in real time. In addition during manufacturing, customers can have access to the up-to-date state of the product to see its progress during production.

Comments: All the presented applications address tracking or doing simple checks on products using RFID. However, they do no offer a complete set of solutions to detect production line errors.

2.2 RFID applications for other domains:

2.2.1 ASSIST - Automated System for Surgical Instrument and Sponge Tracking

In [18] Rivera et al. developed an RFID based automated system for tracking sponges that are used during surgeries. During medical surgeries, the problem of forgetting objects inside a patient's body might lead to his death. With all the caution taken by nurses and doctors, miscounting the sponges or other errors would bring the problem back. Reports estimate that it might happen once in every 1500 surgeries. ASSIST solves this problem in a reliable and feasible manner. The system uses low frequency RFID because the readers in this case can read tags even if they are inside the patient body and covered with different body fluids or organs. Also, they are reliable when used in an environment surrounded with metal tool e.g. surgical tools. Sponge tracking starts at a check-in station. It verifies that all sponges in a package are available and registers them in the database for future usage in the tracking process. When the system initiates, the number of available sponges are displayed on the GUI. After the doctor has used a sponge, he should discard it by putting it in a bucket that signifies a check-out station. The number of discarded sponges and checked-in sponges is updated when a sponge is discarded and then displayed on the GUI.

2.3 RFID based complex event processing: models and middlewares

2.3.1 RF^{2}ID: A Reliable Middleware Framework for RFID Deployment

In [19] the authors propose a reliable middleware framework for RFID deployment. The framework focuses on reliability issues of RFID systems. The framework is dedicated to support path-based object detection including object tracking and object location. According to the authors, the major factors that affect the reliability of such systems are: RF interference, deployment environment, configuration of the readers and placement of readers and tags. To resolve the lack of reliability they developed two concepts: (1) an abstraction layer that lays above the RFID physical readers, it hides all the possible errors or false readings. This layer represents a virtual reader that holds correct and pure RFID events and participates with other virtual readers to manage the flow; (2) a production path abstraction (virtual path) that is made up of several virtual readers. System architecture: the core component of the system is a virtual reader. Each virtual reader on the virtual path holds five lists of tags: (1) a list of observed tags, and each one is associated with the physical reader that has read it (2) a list of received tags containing the a filtered version of the observed tags (3) a list of expected tags to be received in the near future on the current path, the virtual reader build this list based on the information it receives from its neighboring VR (4) a list containing missing tags, those tags are the ones that are expected but never received (5) a spurious tags list containing tags that have been observed but was not expected. These lists support the responsibilities of a VR of data, path, and query management. Moreover, a collection of physical readers is connected to each VR. And each of these sets (PRs and a VR) is distributed to cover a geographical area over the virtual path. VRs have three management tasks: (1) data management (2) path management (3) query management. In their work, they did several evaluations on the reliability of physical readers, as well as the reliability of their system under different conditions. The results showed that the number of detected tags from within a collection of tags increases when the power of the physical reader increases and the distance between the antenna and the tags is decreased. Also, the number of missed tags decreases at the VR level compared to individual PRs. As well, increasing the number of VRs along the path reduces the number of missed tags.

2.3.2 Study of CEP based RFID data processing model

In [20] the authors designed and developed a CEP system called BCEPS. The system deals mainly with two challenges that RFID events based systems raise: (1) processing of low level events coming from readers, (2) the construction of high level event that are appropriate for business needs out of the basic events. Primitive events, which are captured by readers, pass through two processing phases. The first phase the data stream processing. In this phase a processor accepts raw events, which includes reader id, tag id, and a timestamp, from RFID readers then removes duplicates and filters conflicting events. The output of this phase is the filtered primitive events. And it is the input for the next phase: complex events construction. In this phase an event constructor accepts the filtered primitive events from the first phase as inputs. Then it constructs complex events according to the complex event language rules. And then sends them to the application . The architecture of the system extends over five layers: (1) device layer, (2) data stream processing layer, (3) event processing engine, (4) data storage layer, (5) application layer.

- Device layer: it encompassed the RFID readers and the tags. When a reader senses a tag it sends it to a temporal data cache as a primitive event that consists of reader id, tag id, and timestamp.
- Data stream processing layer: responsible for filtering, cleaning and removing duplicates of the raw events received from the device layer. And for preparing and organizing primitive events and include additional data, which is important to the application, such as employee number.
- Event processing engine: embraces an event constructor component that constructs events based on the retrieved primitive events and on the GUI events from the application. It included

a priority to each event. In addition, the engine includes an event processing system that processes events according to their priority.

- Data storage layer: stores related data to support querying additional information related to events.
- Application layer: sends GUI events to the event processing engine. As well, it manages and organizes the results, which are produced by the event processing engine, and shows them on the display.

2.3.3 Design of RFID middleware based on complex event processing

In [21] Dong et al. present a design of an RFID middleware base on CEP. The design focuses on the real time requirements of RFID. In their design they focus on four main principles that build up the middleware: (1) caching strategy (2) reporting past events (3) patterns appearing in RFID events (4) CEP reports for subscribers. Following is an overview of the components of their proposed system. Reader adapter: the reader driver that manages and controls it. It is an interface between readers and the middleware that creates a flow of raw events as an input to the cache. Cache strategy: it is used to handle the real time requirements of managing and acting upon RFID events as well as improving the performance of the system. The adopted strategy in this design is the Real Time in memory event database. The concept is equivalent to the cache concept in computers. Fast memory stores frequently used events, whereas slow memory stores all other events. Event processor manager: it is responsible for managing the core components of the system: event processors. They contain all the required event processing functionalities such as filtering, aggregation, grouping, and detection of complex events. The manager is also accountable for confirming their performance. Subscriber manager: the system uses publish-subscribe scheme to communication with subscribers. The manager sends events reports to subscribers as well as to the active database. Active database: passive databases respond to the user's query with the required information whose description is formulated in the query. Whereas, active databases wait until a predefined action happens on the data e.g., a certain transaction takes place or new data is inserted into the database. In this design, it stores events reports and sends them to reader adapter for analysis. The work in [21] describes the principles of designing and implementing an RFID CEP middleware system. It integrates several techniques and methods to reach the goal of meeting real time requirement of RFID events processing.

2.3.4 Complex event processing in enterprise information system based on RFID

In [22] Zang and Fan proposed an architecture for RFID event processing in enterprise information systems. They identify two gaps in the current information systems: one is the gap between the real world situations and its representation in the virtual world; and the other is the gap between the basic, simple and raw data acquired by sensors and readers; and the higher business level logic and events. the purpose of the proposed architecture is to leverage these two gaps. In their work, they formulate a meta model, context, rules operators and event processing of the architecture. An event does not exist by itself, on the contrary it is connected to its context, it has operators and it comes from different resources. Rules for cep: they define a cep rule as: ”EVENT (complex event pattern) IF (qualification) DO (action)” for a complex event pattern an action is triggered if the conditions of the qualification are satisfied. Within a pattern detailed information is specified using pairs of operands and operators. The system has three types of operators: (1) Time operators (2) Causality operators (3) RFID operators.

2.3.5 Complex event processing in RFID Middleware: a three layer perspective

Hu et al.[23] view an RFID system as four components: tag, interrogator, middleware, and application. in their paper they discuss CEP in RFID middleware from a three layers viewpoint: (1) logic structure, (2) temporal constraint, (3) event detection. They propose a model based on petri net for each layer. And they suggest it as a guide for implementing a CEP engine in RFID middleware.

They developed a concept model for RFID events. An event can be primitive or composite when it combines two or more primitive events having a relation of one of six operators (constructors): aggregation, disjunction, conjunction, negation, sequence, and within.

2.3.6 Commnets

The five systems, which were presented in this section, discuss the modelling, the design, and the development of RFID based CEP middlewares. In this thesis I do not develop a CEP middleware, instead I use Esper[4] CEP engine to discover RFID patterns and detect errors.

2.4 RFID reliability

2.4.1 RFID in metal environment

In [24] Arora et al. studied the effects of metal on the performance of RFID at ultra-high frequency (UHF). In their work they addressed the problem in two parts: (1) near field of reader antenna, (2) far field of reader antenna. In their experiments, they setup a metal sheet and attached a tag to it. A robot holds the reader and moves in front of the tags within a certain area. For each position of the reader they recorded whether it read the tag or not. They found that for different metals the reading reliability is different. They compared three types of metals: Brass, Aluminum, and mild steel. For reading reliability, mild steel settings gave the highest reading rate. Aluminum came second and Brass came third. To improve the reading reliability they used three techniques: (1) using a spacer between the tag and metal, (2) providing offset to the tag, (3) angled tag (lifting it from one end). The first technique showed huge improvement on the reliability. The second and third techniques improved the reliability, but offered less reading rates than the first technique.

2.4.2 Reliability techniques for RFID-based object tracking applications

In [25] the authors investigated several factors that affect the reliability of RFID system for tracking applications. These factors include: the distance between neighboring tags, distance tags and the reader, the orientation of the tag when attached to an item, the location and the number of tags for an object required for an object. In their work, they focused on passive tags because they have weak signal and a lower read reliability than active tags. They performed extensive experiments and found that the reliability of readings decreases when the distance between the reader and the tags increase. In addition, it increases when the distance between tags is increased. They tested six different orientation settings Figure 2.5, they found that the orientation of tags is very significant for the reliability. Orienting tags perpendicularly against the reader reduces the reliability of reading to its minimum; however orienting tags such that they are facing the reader improves the reading reliability significantly.

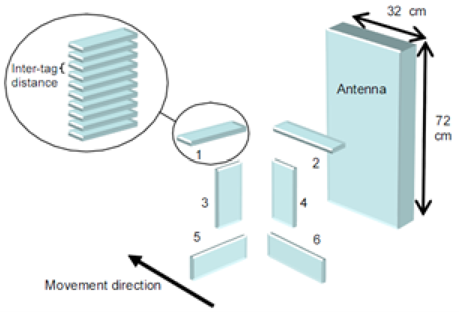


Figure 2.5: Tag orientation and antenna [25]

2.4.3 How to detect cloned tags in a reliable way from incomplete RFID traces

A tag cloning is copying genuine tags and using their value in other (counterfeiting) tags. This activity causes confusion in an RFID tracking and tracing system, financial lose in business applications, in addition to breaking into RFID based security borders. Cryptography is the conventional way of preventing tag cloning. Lehtonen et al. [26] propose a solution to the problem that is based on tracing tags throughout their journey. A genuine tag has a normal predefine behavior, e.g., a tag should be seen in location A then B then C. A cloned tag deviates from the normal behavior of genuine tags e.g., a cloned tag might go from A to C directly without passing through B. Sensing a tag at location A, then sensing it at location B is called a transition from A to B. A probability is assigned to all transitions. The authors used a simulated supply chain and conducted different tests to evaluate their work.

2.4.4 Comments:

The studies in this section investigate the reliability of RFID tags and readers under different conditions. And the effect of a set of factors on the reliability. In this thesis I benefit from the studies to optimize the settings of the RFID system that I use in this thesis.

Chapter 3

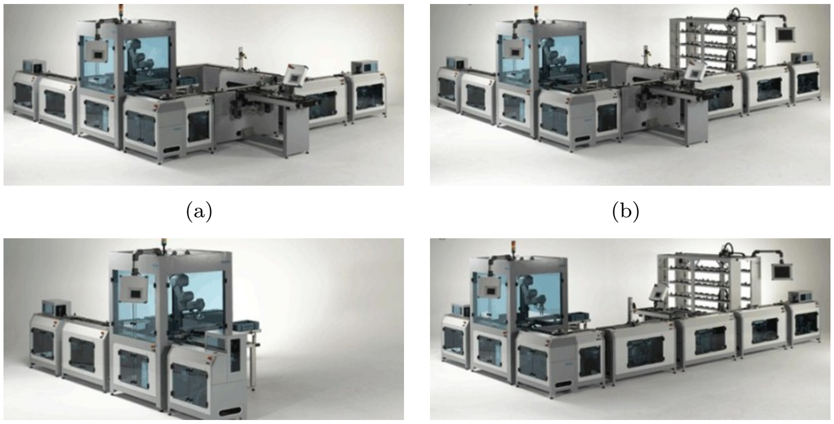
System Architecture

3.1 Lernfabrik

The lernfabrik is a modern factory infrastructure for the purpose of training students on the production process using real products and assembly lines. It is also a good place to practice and evaluate new tools and technologies that have the potential to support and enhance modern factories as well as optimize their operation.

As you can see in the Figure 3.1, several modules are assembled in various topologies to make up the assembly line. Production of products goes through two phases: (1) products assembly planning (2) products assembly. Planning refers to the process of setting up how products are supposed to be assembled in the second phase. Planning includes specifying at which position on the base plate should each part be placed. When producing a single type of products the planning configuration is the same for all products. But in build-to-order production each product has its specifications and configurations. The second phase follows the planning phase. Product parts are stored on shelves temporarily waiting for assembly. The finally correctly assembled product contains three different types of parts see Figure 3.2. Correct assembly of a part means that it is placed at its correct position on the base plate as planned. Labor (workers) and robots are responsible for the assembly of parts. The assembly module is a special type of modules.

In case of human workers, the module is integrated with shelves



(a) (b)

(c) (d)

Figure 3.1: Factory Configurations

containing product parts. A worker stands next to the module and waits for incoming plates. A plate stops waiting for the assembly of one or more parts. Here comes the task of the worker to place the part on the base plate. To update the state of the product the worker has to click on a button on a terminal display in front of him. Partially assembled product moves forward to complete the assembly. And a new base plate comes in taking the place of the previous one and so on. In the case of robot assembly, product parts are arranged inside pallets and the robotic arm substitutes the worker in doing the assembly. It picks product parts from the pallets and places each of them on its position on the plate. Each product goes through three assembly modules. And after it is finally assembled it passes through an image processing based checking to make sure that the first position has not moved during the assembly process. Figure 3.3 shows examples of possible product variants.

3.1.1 System modules

The system has three modules which can be utilized selectively according to the required functionality or solution. The modules are:

1. RFID based complex event processing framework: this module employs RFID readers at certain points at the factory. They sense RFID tags from the surrounding environment. A CEP

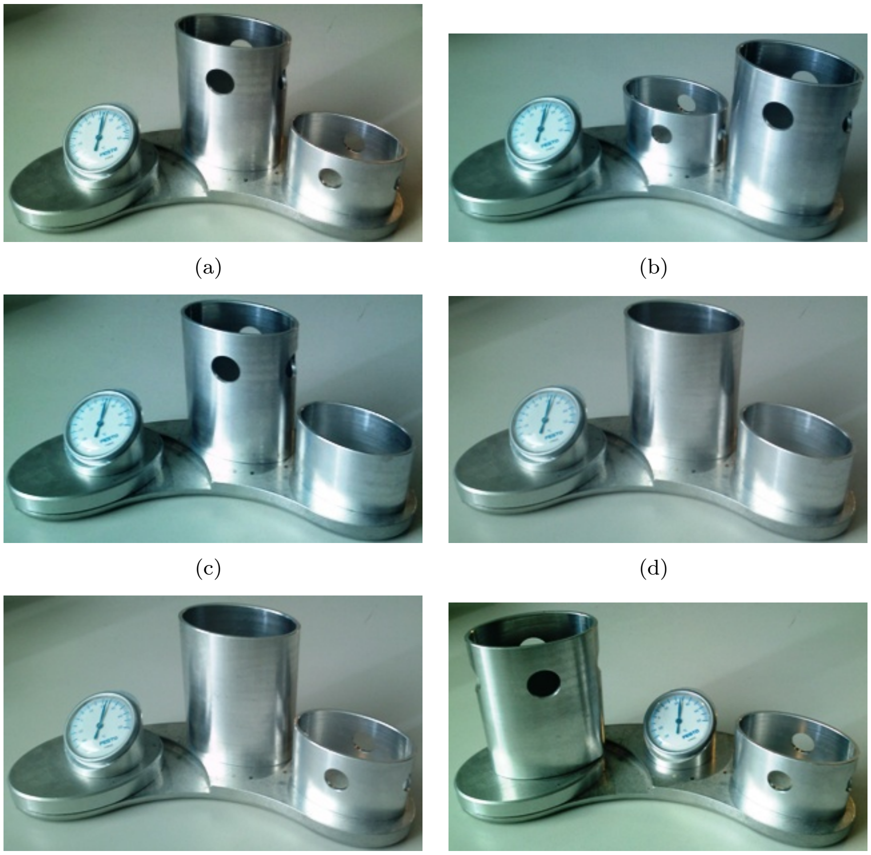
(a) Small Cup (b) Small Cup with Holes (c) Large Cup (d) Large Cup with Holes

(e) Watch, Thermometer or Hydrometer

Figure 3.2: Product Parts Variants

engine accepts events from the readers and looks for patterns within the stream of RFID events. The higher level compound events represent the different errors that might happen during the assembly process.

2. Image processing based error detection: this module compensates for the inability of the first module of detecting the exact position of items on the base plate. It uses a fixed camera to take pictures of the product then it applies an edge detection algorithm to locate the different parts on the plate.
3. RFID based HCI: this module is a simple yet powerful tool to help a worker at the assembly point to assemble the right part at the right position on the base plate. The purpose of this module is to replace the current naïve technique that is being used in the Lernfabrik.



(a) (b) (c) (d) (e) (f)

Figure 3.3: Examples of product variants

Chapter 4

RFID based CEP

4.1 RFID based CEP Framework

Figure 4.1 shows the components of the CEP Framework and their connections. The framework is an extension of a previous work in [14].

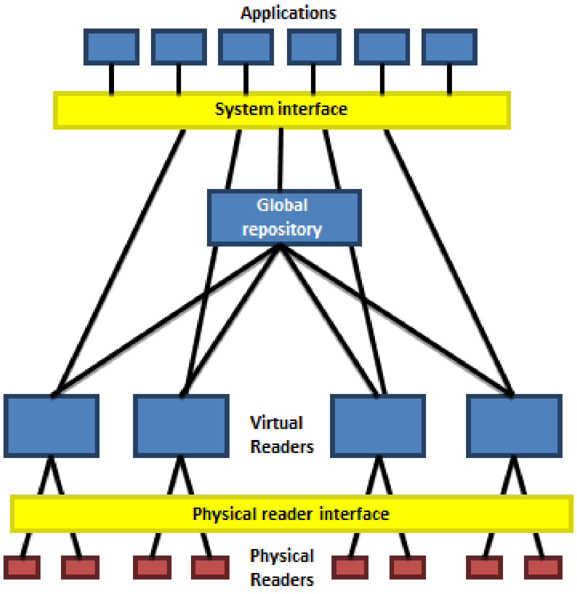


Figure 4.1: RFID base CEP framework

The components of the framework are:

- *Physical readers (PRs)*: represents the RFID readers. Each PR is connected with exactly one virtual reader (VR). They receive raw events from tags moving within their sensing range. Raw events are noisy. They may contain false positives, i.e., events that a PR reads unexpectedly. They arise, for instance, when the PR reads farther away from its expected reading range, or when a worker moves near a PR while he is holding some tags. It is also possible that a PR misses a tag even though it is in its reading range, i.e., a false negative event.
- *Physical reader interface*: represents the medium or the transmission channel through which the events, which are captured by the PRs, are transmitted to VRs.
- *Virtual readers*: represent an abstraction of physical readers. VRs are connected such that each VR receives information from its predecessor and sends information to its successor. PRs are distributed on VRs such that each VR is connected a set of PR. A PR is connected to only one VR. A VR may participate in a local or a global application. Based on the application a VR runs one or more functions. A global application comprises all VRs within the framework, whereas local applications require only a subset of them. An instance of the complex event processing engine Esper runs on every VR. This makes the framework suitable for a scalable and distributed complex event processing of huge amounts of events.
- *Global repository*: no processing activities are done at this level, on the other hand, the global repository holds information about the overall system structure such as the positions of VRs and PRs and their distribution.
- *System interface*: it is the communication interface between the global repository and the VRs on one hand and applications on the other hand.
- *Applications*: generate the business level information for managers or workers. On this level, information is user friendly and it is in its simplest form for easy management and monitoring.

4.2 Events Hierarchy

Figure 4.2 shows the hierarchy of the events within the system.

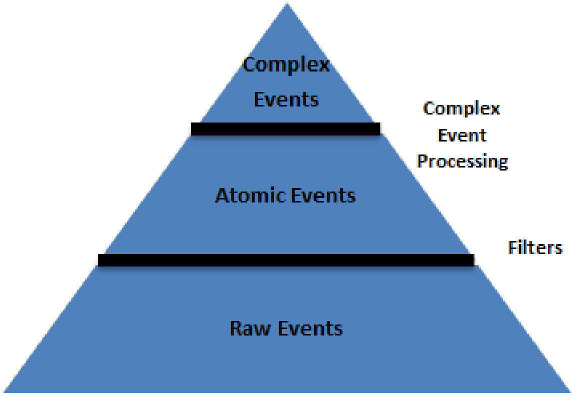


Figure 4.2: Events Hierarchy

- *Raw events*: the first level of events contains all events that a reader reads while it is switched on. Raw events include atomic events and noise. False readings, out-of-order readings, duplicates, and corrupted tags causes the noise. Another type of noise is false negative, i.e., events that a reader does not sense although their corresponding tags are within the reading range of the reader. A raw event is define as: RE=(tag,reader,time).
- *Filters*: they remove any noise from the raw events. The result of filtering raw events is a set of atomic events and they represent the next level of events.
- *Atomic events*: are the de-noised raw events. They are inputs to a complex event processing middleware or engine.
- *Complex event processing*: it is done by a CEP engine which takes atomic events as inputs and then according to event processing rules it generates complex events. Rules are defined according to the application needs and functionality.
- *Complex events*: they are the resulting events of the CEP engine after it process atomic events. These high level events signify the final result of processing atomic events. The type of

a complex event depends on the running application and the processing rules defined for it.

4.3 Consistency Stack

Consistency stack: in a previous work[14] various consistency issues were packed into a consistency stack. To cover additional consistency issues, those that were not covered in[14], I extend the stack to develop into the form of Figure 4.3. Next I discuss its components and interfaces.

RFID consistency substack:

- Duplicates elimination: As long as a tag is in the reading range of the physical reader, it keeps on reading this tag and sending it to the control module. If CEP engine receives a tag twice it process it as two separate events, i.e., it assumes that there are two different objects holding the same tag ID. Therefore, eliminating duplicates is important to identify each object uniquely.
- False readings elimination: false readings stem from reading tags that come accidentally into the reading range of the reader. E.g, when a worker moves near a PR while he is holding a tagged object; then the sensed tag is a false reading and the reader must ignore it.
- Out-of-order readings elimination: they arise when a PR reads a distant tag before a near one.
- Missed readings elimination: they are the result of a reader not reading tags presented within its reading range.

Production consistency substack Ensures that the production process is consistent and makes sure that any possibility for occurrence of assembly errors is detected prior to their happening. However, in circumstances where an assembly error arises, it detects and reports it. It is divided into two substacks: (1) pre-assembly consistency substack (2) post assembly consistency substack.

- Pre-assembly consistency substack: ensures that product parts and semi-assembled products are consistent up to the moment when they reach an assembly point.

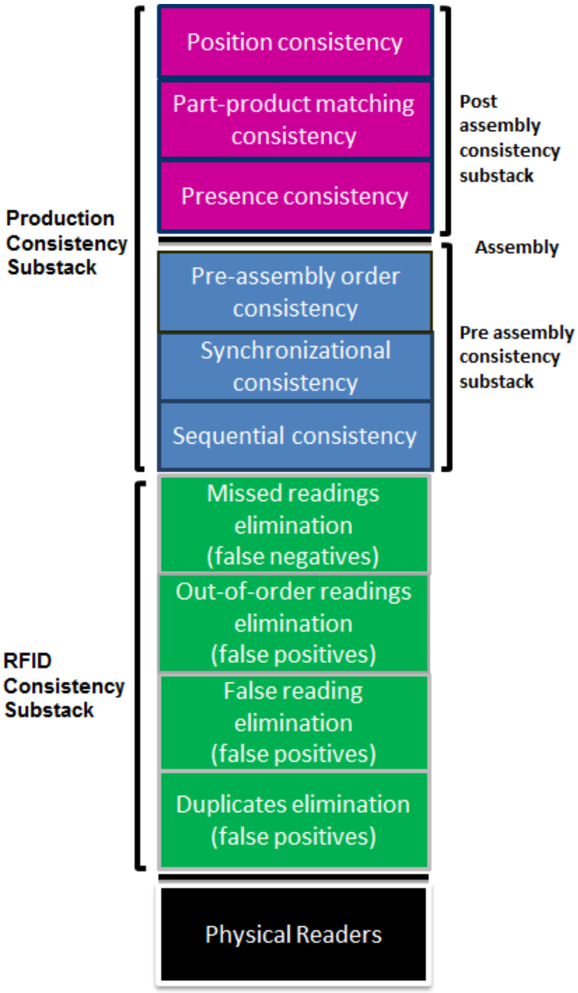


Figure 4.3: Consistency Stack

  - Sequential consistency: ensure that the product parts are moving on assembly lines in the order they were planned to follow.
  - Synchronizational consistency: ensures that two product parts that should meet at the assembly point belong to the same product. i.e., if they belong to different products the resulting product after the assembly procedure is defective.
  - Pre-assembly order consistency: makes sure that a sequence of parts approaching an assembly point (for assembly in sequence) is correct. This is different from sequential consistency where the sequence is very general and parts within it might get assembled each with its specific product. But here the objects are in a small sequence and are going to be assembled together according to that sequence.

- Post-assembly consistency substack: ensures that the assembly procedure went well and no errors resulted after a semi-assembled product reaches an assembly point and goes through an assembly procedure.
  - Presence consistency: makes sure that the recently assembled product part is present and assembled with the product.
  - Part-product matching consistency: ensures that the recently assembled part is of the same product type as the product to which is was assembled.
  - Position consistency: ensures that the product part is in its correct position and assembled in the right place on the product. Position consistency already covers presence consistency, but in situations where the position of an object is not important the presence consistency is sufficient.

4.4 Factory objects and RFID events management

- Product: each product has an ID, a class and a description. The ID distinguishes each product from other products. A

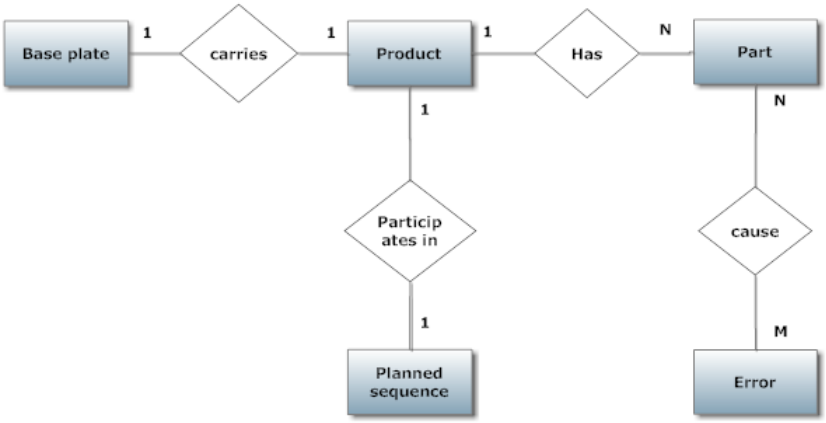


Figure 4.4: ER diagram of the management components

class describes a set of products with similar characteristics.

Product ID	Product class	Product description

- Product Part: each product part has an ID, a class and a description. The ID distinguishes each product part from other products parts. A class describes a set of product with similar characteristics. The product ID refers to the product to which this product part belongs.

Part ID	Part class	Part description	Product ID

- Planned sequence: parts, which are moving on the assembly lines, have a particular order. Each part in the sequence has an RFID chip attached to it. Therefore, it has a tag ID referring to the chip's tag. Also, it has a global sequence number that indicates its position within the sequence on the assembly line. the local sequence number indicates its assembly order position within a product.

Tag ID	Global sequence number	Local sequence number	Part id	Product id

- Assembled parts: after a worker assembles a part at its place, the system detects this action and an entry is inserted into the assembled parts table using the part ID and a t imestamp.

Part id	timestamp

- Errors: when the system detects an error; an entry is inserted into the errors table. Depending on the type of the error different fields are filled, otherwise they are set to null.

ID	Part1	Part2	Virtual Reader 1	Virtual Reader 2	Timestamp	Error type

- Base plate table: items are put on plates according to the assembly point (AP). Tag ID is the tag of the RFID chip attached to the plate. AP fields contain instructions for workers in different point on what part should be assembled in which position on the plate. E.g., AP1= 1:1 means that part of class 1 should be assembled in position 1. Another example: AP2= 2:3 means that part class 2 should be assembled in position 3.

tag ID	Plate id	Product id	AP1	AP2	AP3

4.5 RFID Based Complex Event Processing in the Smart Factory

In this section I discuss how the system detects different errors. For each error i will discuss: (1) the cause of the error, (2) problems that result if the error take place, (3) the atomic events pattern of the error, (4) the query used to detect the error using Esper. The discussion will cover the following errors:

- Pre-assembly errors:
  - Sequence errors
  - Synchronization errors
  - Incorrect pre-assembly order errors
- Post-assembly errors
  - Missing parts errors
  - Part-product mismatch errors
- Delay errors

4.5.1 Sequence Errors Detection

In build-to-order production product parts for various products move on the same assembly line. The moving sequence of these parts should be in accordance with their assembling order. This ensures that each product part is assembled with the correct product matching the predetermined plan. Errors in sequence result with wrong assembly for products. E.g., a product part is assembled with the wrong product. Therefore, any error in the sequence must be detected as early as possible to avoid any future defective products or any complications in the production process. Each part has a sequence number. The first part can have any initial value and the sequence number of the immediately following part is incremented by one and so on for the following parts. E.g., the sequence of parts p1, p2, p3, and p4 should have the sequence numbers: 1, 2, 3 and 4 respectively or perhaps 55, 56, 57, and 58. The CEP engine takes two successive atomic events, e.g., e1 and e2 (e1 comes before e2). Then it compares their sequence numbers, if the sequence number of e2 does not equal to the sequence of e1 plus one then engine generates a sequence error complex event and an entry is inserted in the errors table.

EPL Pattern:

```
 pattern (A B)
 define
B as       not(B.globalSequenceNumber =A.globalSequenceNumber+1)
           and (A.readerId='PRx') and (B.readerId='PRx')
```

4.5.2 Synchronization Errors Detection

Assembly points connect two assembly lines. One line contains various product parts and the other contains the partially assembled product (or initially an empty plate and no part are assembled on it). In case an error has occurred such that the wrong part arrives at the assembly point then a wrong assembly would happen, i.e., a wrong part is assembled with the product in the assembly point. And it is now a defective product. The system detects a synchronization error by checking the product ID of the two incoming object at the assembly point. Each assembly line is assigned a reader. Each one reads the tag of the objects approaching the assembly point. If the products ID of the two objects are not the same, then a synchronization error is raised. E.g., a pattern like (e1 e2) with product ID of e1 is prod1 and the product ID of e2 is prod2, then Esper raises a synchronization error complex event and an entry is inserted in the errors table.

EPL Pattern:

```
pattern (A B )
define
B as      not(B.productId =A.productId ) and ((A.readerId='PRx')
          and (B.readerId='PRy') or  (A.readerId='PRy')
          and (B.readerId='PRx') )
```

4.5.3 Incorrect Pre-Assembly Order Errors Detection

The sub module checks the local sequence number of two successive events. Two cases are considers: (1) the product part is the last part in the sequence, (2) the product part is not the last part in the sequence. For the first case the module checks the current part and the next one. The latter should be of a different product type of the former, because after detecting the last part of a product the next part should be of a different product. Otherwise an error has occurred. Furthermore, to make sure that the next set of product parts, which belongs to the next product, is starting with the correct product part, i.e. the first product part of the next product; the query checks that the sequence number of the next part is equals to one. However, if all parts are assumed present on the line and none of them are missing; the last check is unnecessary. For the second case the query checks the two successive events, if their product ID does not match or the local sequence number of the second one does not equals the local sequence number of the first one plus one; an incorrect product part order assembly error is raised. E.g., consider the assembly process of two products, each product has four parts. Parts should be assembled in order. Let product 1: e1, e2, e3, e4; product 2: e5, e6, e7, e8. Each product part has a local sequence number according to its assembly order. For product 1, e1, e2, e3, e4 get 1,2,3 and 4 as sequence numbers respectively. For product 2, e5, e6, e7, e8 get also 1,2,3 and 4 as sequence numbers respectively. Assume that the first two parts of each product comes from assembly line 1 (AL1) and the next two parts comes from AL2 and the parts for the first product are coming first. The correct sequence should be e1, e2, e3, e4, e5, e6, e7, e8. Such that, the first product is assembled correctly then the second one is assembled after that correctly. Any error in this sequence will result in incorrect product part order assembly either for product 1 or product 2. When an error is detected, Esper raise an error signal and insert a new raw in the error table.

EPL Pattern:

```
pattern  (A B)
define
B as     ((A.readerId='PRx') and (B.readerId='PRx'))
         and (A.localSequenceNumber!=3 and (A.productId!=B.productId
         or A.localSequenceNumber!=B.localSequenceNumber -1))
         or (A.localSequenceNumber=3 and (A.productId==B.productId
         or B.localSequenceNumber!=1))
```

4.5.4 Missing object detection

A product part goes missing if a worker forgets to assemble this part to its product. This results with a defective product. The reason behind this is the physical or mental stress of the worker due to the repetitive task he is doing. Detection of a missing object is done using two physical readers: reader 1 and reader 2. When a plate reaches the detection point reader 1 detects its presence. Then it sends a signal to the system indicating the presence of a plate. Then the control module starts reader 2 for a predefined period of time. Reader 2 begins reading the tags of objects on the plate and then sends them to Esper. Based on the number of tags, Esper detects whether an object is missing or not. The correct number of tags, which are supposed to be assembled at this detection point, is predefined according to the location of the detection point.

EPL Pattern:

```
SELECT count(distinct productID) as count
```

```
FEOM RFIDEvent.win:time(5 sec) where readerId='PRx'
output last every 5 seconds
```

4.5.5 Part-product mismatch detection

Due to human errors a product part might be assembled with the wrong product. The resulting product is a defective one. Detection of mismatches soon enough would bring the opportunity to correct the flaw before the product continues its assembly process. The detection of mismatches uses also two readers just as the detection of missing parts. Reader 1 reads the tag of the plate and sends it to the control module for further processing. The control module queries the database to get the product ID associated with the plate tag ID. It also starts reader 2 to begin sensing the available tags on the plate. It then checks the product ID associated with each of these tags against the product ID of the plate. In case a product part has a different product ID than the plate product ID; then there is a mismatch error and a new entry is inserted into the errors table.

EPL Pattern:

```
SELECT *
FROM pattern [(every A=RFIDEvent(productId='PRODx'
and readerId='PRx'))
WHERE    timer:within (5 seconds)] ";
```

4.5.6 Delay Detection

In continuous products assembly parts move in a predefined speed on the assembly lines. Mechanical failures could cause the assembly lines to stop moving or to become slower for a period of time. Detection of delays at the right time ensures a smooth and progressive production operation. To detect delays using RFID, an RFID reader is placed near the assembly lines. The reader is supposed to read a tag every N seconds. It continuously checks for the absence of events for a predefined period of time e.g., 5 seconds. The absence indicates that there is a delay in some parts of the assembly line, perhaps due to congestion in an earlier stage of the line or a mechanical failure.

EPL Pattern:

```
pattern [every (timer:interval (5 sec))
        and  not a=RFIDEvent(readerId='PRx')    ]
```

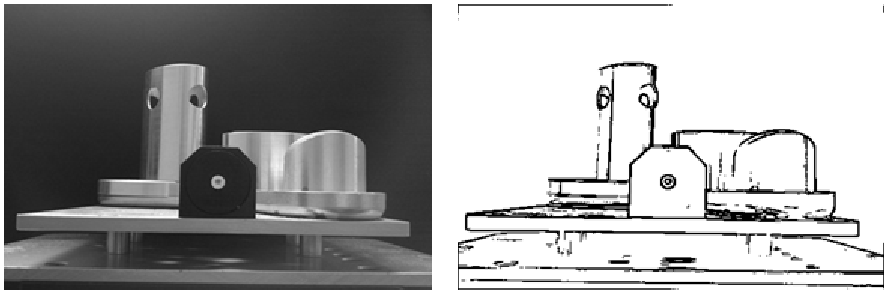
Chapter 5

Image Processing Based Error Detection in Lernfabrik

In digital image processing, an edge is a set of connected pixels connecting two distinct intensities of an image along a particular orientation. An edge represents the degree gray-level transition when its intensity changes. Mathematically the rate of change is computed using the first derivative. For a two variable function, such as the intensity function of an image, it is computed using the gradient vector.[29] Edges of items inside an image help locating the items by locating their edges.

When the worker assembles a product part in the wrong place of the product the resulting product has the part on it already but it is defective because of the wrong assembly. An example from the Lernfabrik products is to place a large cup on the second position instead of the first one. Detection of this type of error is not possible using RFID based CEP, because RFID can detect the presence or absence of a tag, but can't determine exactly where the tag is when the tags are within a small area. Therefore, this type of error can't be detected using the previously mentioned techniques. To detect such errors I am using an image processing based technique. I am using a fixed camera to capture images of the plate with product parts on it. In order to detect errors as soon as possible the camera is located after every assembly point. I am also employing the same technique to detect if a part, which is assumed to be assembled a while ago, is actually present or missing (the previously referred to as missing object detection).

Incorrect part position and missing part detection: According to a specific parts placement plan, parts should be place on specific places on plates. Each plate has three sockets. Shelves containing different parts are located in front of the assembly line at the assembly zone. A worker grabs a part from the shelves and places it on its specific position on the plate. If the worker puts it on the wrong place; a misplaced part assembly error occurs. Besides, if he forgets to put it on the plate; a missing part assembly error occurs. To detect such errors I used an image processing based edge detection algorithm. I used it to discover the positions of the different parts as well as their presence of absence. After I have investigated many images of the plate with the parts on it at different positions, I discovered nine featuring regions that I used to discover the previously mentioned two errors. The algorithm of detecting errors is described in pseudo code in Algorithm 1.



(a) Gray Scale Image (b) Applying edge detection algorithm

Figure 5.1: Applying edge detection algorithm

First, an image of an in-progress product is transformed into a gray scale image. Then the Sobel operator is applied to it. The resulting image is a black and white image that shows edges as white pixels within an overall black image. Each of the three positions on the baseplate may contain a thermometer, a small cup, or a large cup. Using their relative length, the algorithm looks for edges (white

Algorithm 1 Detect errors

```
$itemAt \leftarrow array[3]$;
$positionsCount \leftarrow array[3][3]$;
$I \leftarrow readImage()$;
$J \leftarrow grayScale(I)$;
$BW \leftarrow applySobel(J, 128)$;
$positionsCount \leftarrow countPixelsInRegions(BW)$;
$initlalize(itemAt, 0)$;
for $position = 1$ to 3 do
  for $item = 1$ to 3 do
    if $positionCount[position][item] > THRESHOLD$ then
      $itemAt[potisoin] = item$;
      BREAK;
    end if
  end for
end for
```

pixels) in each position starting from the top looking first for the large cup, if not found it goes to the next level to look for the small cup, if not found it foes to the last level to look for the thermometer. If none of the parts was found then it declares the position as empty. The position check is repeated for the second and the third positions. And the results of the algorithm are the exact type of item in each of the three positions, a large cup, a small cup, a thermometer, or the position is declared empty if none of the parts was found. This result is compared to the planned positioning of parts, in case of any alternation to it; a misplaced part error is detected, on the other hand, if a part is missing whereas it is assumed to be assembled; a missing part assembly error is detected.

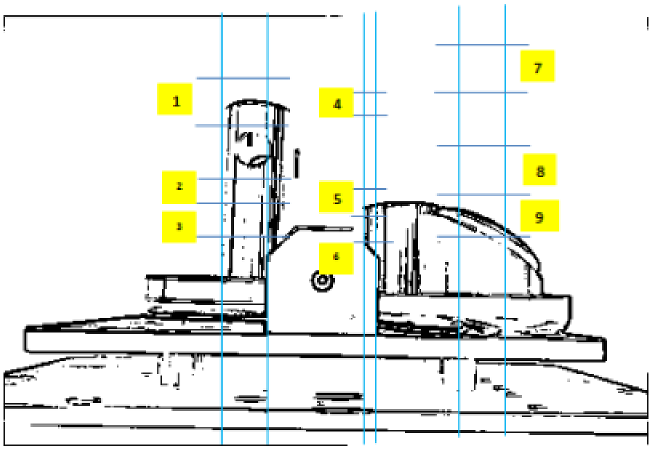


Figure 5.2: Image features

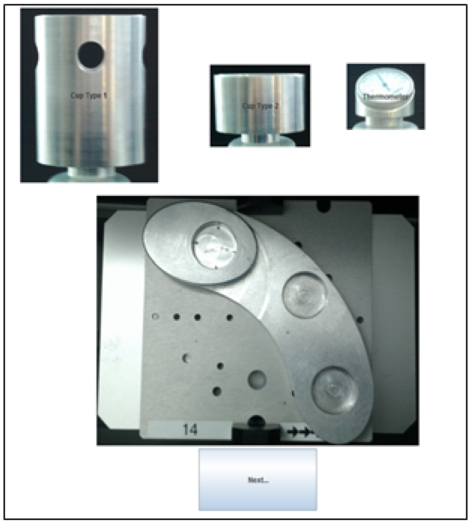
Chapter 6

RFID Based Assembly Assistance for Workers in the Smart Factory

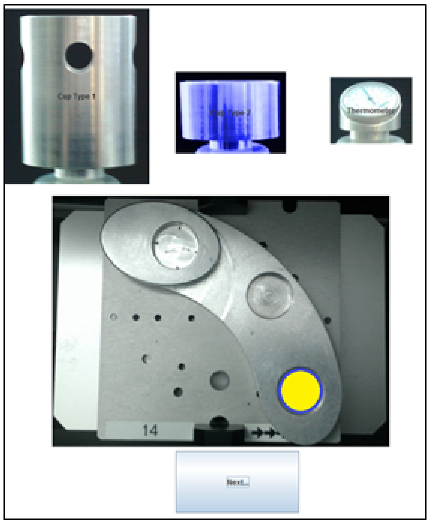
In the Lernfabrik each plate approaching an assembly point has its own customization, i.e., it has its own set of parts and each part has to be assembled in a specific position on it. And this differs from a product to another. As I explained previously each part is assembled to the plate at a different assembly point. The current settings assume that each class of parts has to be assembled at a predefined assembly point. E.g., the large cup with holes will be assembled at assembly point A and the small cup with no holes will be assembled at the assembly point B. When a plate approaches an assembly point the RFID reader reads the tag of the plate then a screen displays an option for the worker asking if he wants to have instructions about the subassembly. If the worker asks the system for help, it shows the ID and the position of the product part that he has to assembly. In addition, the worker has to press a button after he assembles a part, indicating that the part is assumed to be assembled. And the system updates its state then moves the plate forward and lets a new plate to come for assembly.

This module utilizes an RFID system and visual animations to instruct the worker on which part should be place at which position on each coming plate. It consists of an RFID reader connected to a computer that displays visual instructions to the worker. In this module I assume that each set of parts belong to a class, e.g, class X contains all large cups, class Y contains all large cups with holes, etc. And each plate has parts associations that represents an assembly step and must be done at a predefined assembly point, e.g., assume that plate 1 has the associations: 1:X;2:Y;3:Z this means that position 1 on the plate must have a part of class X, position 2 must have a part from class Y and position 3 must have a part from class Z. Furthermore, associations for all plates are stored in a database. When the reader detects an approaching plate (by sensing its tag) it sends the tag ID to the computer. Then it acquires its association for the current assembly point from the database. According to the association, the module flashes the associated part corresponding to the part in the association as well as the corresponding plate position. Figure 6.1.

The old settings requires the worker to keep in mind the IDs of all parts. But in case the the number of parts variants is very large this would be very difficult for the worker. Moreover, because of the repetitive task, the worker might incorrectly read the part ID or position. Therefore, this module will reduce the time that the plate spends at assembly points and will reduce the assembly errors in case of a high number of variants.



(a) Initial state



(b) Blinking part and position

Figure 6.1: GUI for the worker

Chapter 7

Evaluations

In this chapter I present the evaluation of the system. First I will present the setup of the system and the environment to conduct the evaluations. Second I will show the performance of the physical readers under different settings. Third I will discuss the performance of the system (in regard of errors detection) under the optimal setting and the effects of false positives and negatives on it. And finally i will present the evaluation of the image processing based error detection module.

7.1 Configurations setup

In the Lernfabrik I used seven modules to build a single-straight assembly line. I used a single virtual reader connected with one or more physical readers that are mounted on the modules as necessary. I used a T61 *lenovo* with 4-GB of RAM laptop as a virtual reader and Volaré UHF USB readers[28] as physical readers.

7.2 RFID readings reliability

Several factors affect the reliability of RFID readings (1) the distance between the reader and the assembly line (2) the power value used for the reader (3) the presence of other readers within its sensing range (4) the number of tags within its reading range (5)the dimensions of the tags (6) the inter-distance between two consecutive tags (7) tag placement on the object (8) tag orientation. In the following subsections I will discuss each factor and show how it affects the reliability of RFID readings.

7.2.1 Tag placement

In [25] the placement fashion of tags on metal was investigated. I have tested two settings: (1) using a spacer, (2) attaching part of the tag and leaving the other part. Figure 7.1 shows the effect of each setting on the number of false negatives.

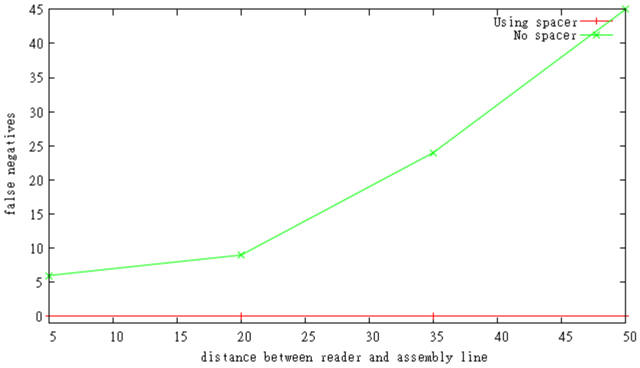


Figure 7.1: Effect of tag placement on false negatives

As you see the number of false negatives decreases dramatically when the tags were attached to the items using spacers.

7.2.2 Differences among readers

To recognize the difference between the readers I have investigated three different readers. Figure 7.2 shows the differences among them when the power is varied.

The number of missed tags differs from reader to reader. For values less than 13 dBm, reader C has the lower number of false negatives for the same power value.

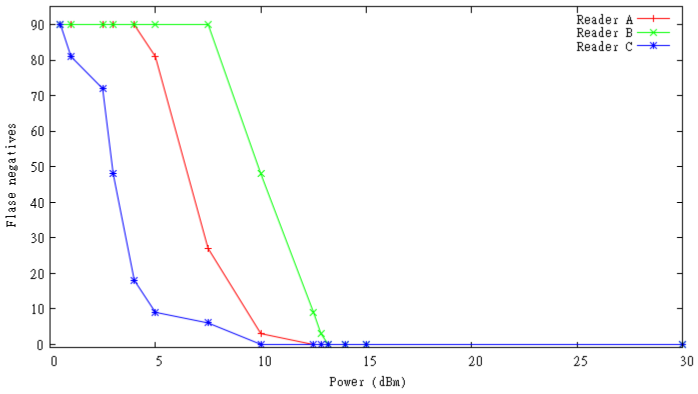


Figure 7.2: Performance of different readers when varying power value

7.2.3 Number of objects within the reading range

Here I used reader B to examine the effect of increasing the number of objects within the reading range of the reader. I used a single tagged part and three tagged parts. When a single part was used, the number of false negatives was slightly less than the number of false negatives when three parts were used. Figure 7.3

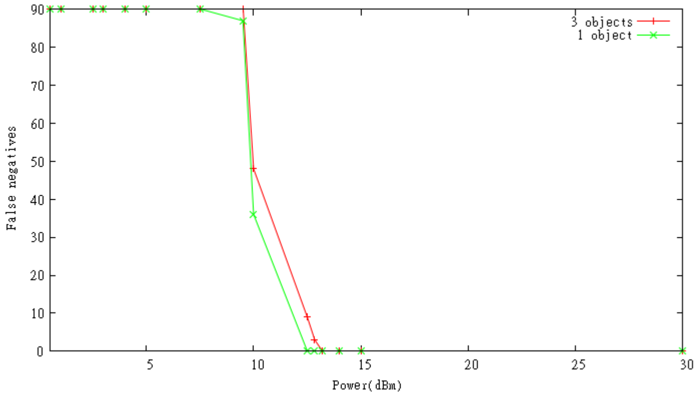


Figure 7.3: Effect of number of objects on the reader's performance

7.2.4 Tag orientation

To study the effect of changing tag orientation on out-of-order readings I used two orientation settings: (1) tags are attached to items such that they face the reader antenna when they pass in front of it, (2) tag are attached randomly. The results show that random placement causes out-of-order readings. Figure 7.4

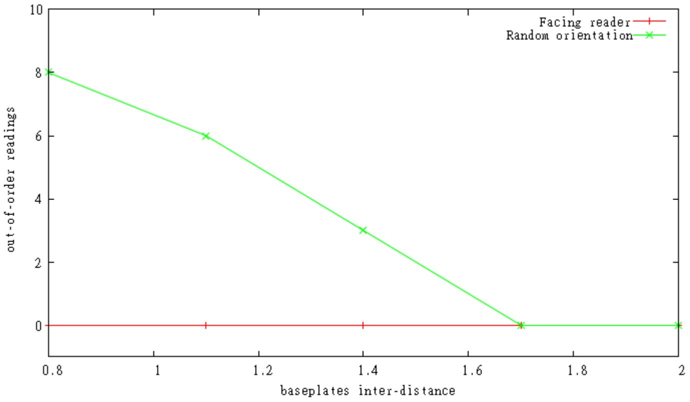


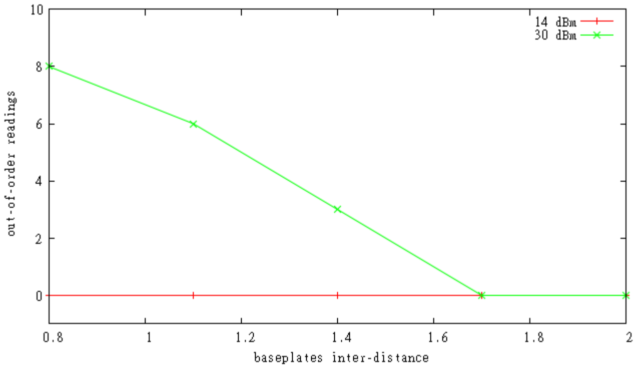
Figure 7.4: Effect of tag orientation on the out-of-order readings

7.2.5 Reader power

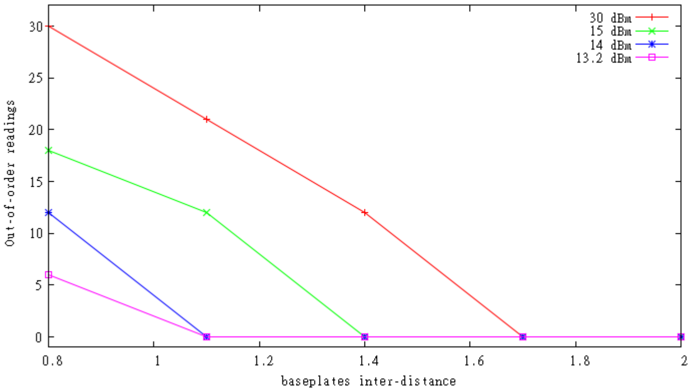
To eliminate out-of-order readings I used another power value. The results show that using 14 dBm eliminated all the out-of-order readings. To examine further the effect of varying power on the number of out-of-order readings I used three tagged items per baseplate. I used four different powers. And for each value I changed the distance between every consecutive baseplates. The results (Figure 7.2.5 show again how reducing power eliminates the number of out-or-order readings.

7.2.6 Another reader in the reading range

I studied also the effect of putting a reader in the way of another reader on the number of out-of-order readings. The results show that the reader that is closer to the incoming sequence has more



(a) Single tagged object



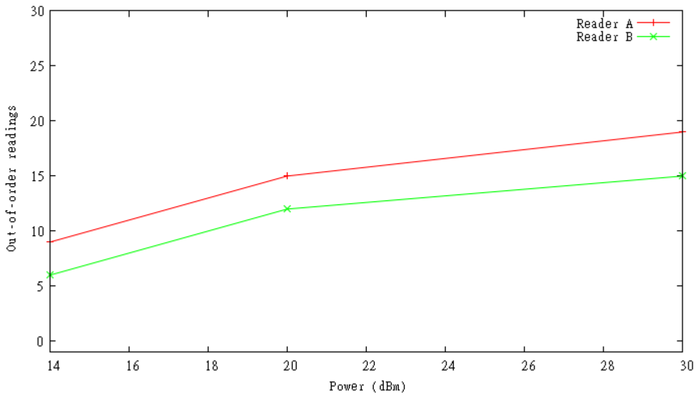
(b) Three tagged objects

Figure 7.5: Effect of varying power on the out-of-order readings

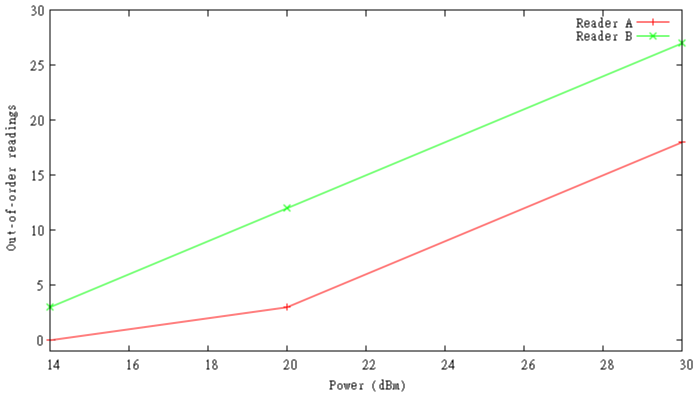
out-of-order readings than the other reader. I tested this effect for readers A and B. Figure 7.6(a) shows the results where reader A is closer to the incoming sequence. Figure 7.6(b) shows the effect when reader B is closer to the incoming sequence.

7.3 RFID based CEP performance under different settings

In this section I discuss how false negatives and false positives influence the detection of each type of errors.



(a) Reader A ahead of Reader B



(b) Reader B ahead of Reader A

Figure 7.6: Effect of having a reader ahead of another reader

7.3.1 Sequence errors

- *False negatives(missed tags):* If the reader misses tags from a sequence of moving tagged objects then the system will detect false errors and true errors might not be detected.
- *Duplicate readings:* If duplicate readings are allowed then the system will detect false errors.
- *Out-of-order readings:* If the reader reads tags out of order then the system will detect false errors and true errors might not be detected.
- *False readings:* If the reader reads tags that it is not supposed to read then the system will detect false errors.

7.3.2 Synchronization errors

- *False negatives(missed tags):* If the reader misses tags from a sequence of moving tagged objects then the system will detect false errors and true errors might not be detected.
- *Duplicate readings:* If duplicate readings are allowed then the system will detect false errors.
- *Out-of-order readings:* If the reader reads tags out of order then the system will detect false errors and true errors might not be detected.
- *False readings:* If the reader reads tags that it is not supposed to read then the system will detect false errors.

7.3.3 Pre-assembly order errors

- *False negatives(missed tags):* If the reader misses tags from a sequence of moving tagged objects then the system will detect false errors and true errors might not be detected.
- *Duplicate readings:* If duplicate readings are allowed then the system will detect false errors.

- *Out-of-order readings:* If the reader reads tags out of order then the system will detect false errors and true errors might not be detected.
- *False readings:* If the reader reads tags that it is not supposed to read then the system will detect false errors.

7.3.4 Missing parts errors

- *False negatives(missed tags):* if the reader misses tags from a group of objects, which are under examination, then the system will generate false errors.
- *Duplicate readings:* allowing duplicates will not affect the detection of missing parts.
- *False and out-of-order readings:* in this case the reader will detect more objects than it is supposed to detect, therefore, the system will detect false errors. Also, in case there is a true error, i.e. an object is missing and the reader reads a false reading, the error will not be detected.

7.3.5 Part-product mismatch errors

- *False negatives(missed tags):* false negatives does not has no effect on detecting this type of error.
- *Duplicate readings:* allowing duplicates does not affect detecting this error
- *False and out-of-order readings:* they cause false errors.

7.4 Evaluation of image processing based error detection

For the evaluation I captured 600 images taken from three different locations at the factory. And I applied brightness levels between

-100(very dim) and 100(very bright). The system was able to correctly classify images when the brightness level were between -50 to 50 (Figure 7.7).

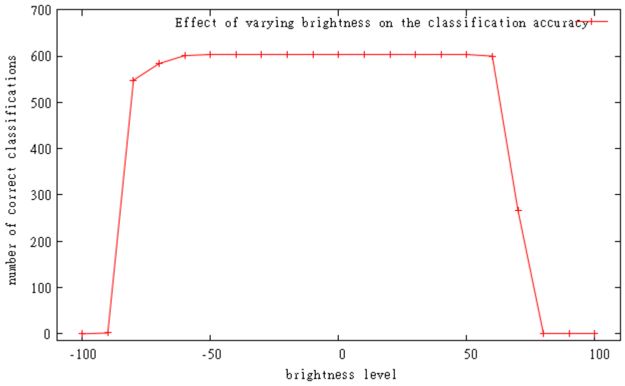


Figure 7.7: Effect of brightness on correct classification

Chapter 8

Conclusion

In this thesis I have built and developed reliability solutions for a smart digital factory using: RFID based CEP, image processing based error detection and RFID based HCI. Solutions covers detection of pre-assembly errors and post-assembly errors. In addition to visual instructions for workers at assembly points. I have deployed and evaluated them in the Lernfabrik which is a real manufacturing environment for training, teaching and applying manufacturing concepts. To help workers doing an assembly step correctly, an RFID reader senses an incoming product, sends its ID to the computer to determine what should be done to it. Then it shows on a screen the required assembly procedure. To detect errors, RFID readers are distributed along the assembly line. Each reader participates in a specific function. The system detects sequence errors, synchronization errors, pre-assembly order errors, missing parts errors, part-product mismatch errors. It detects positioning errors using image processing by locating the exact position of a product part using Sobel edge detection operator. Reliability of the system depends on the reliability of the RFID readers and tags which is affected by several factors. The RFID system operates reliably and effectively when the the settings for the RFID components are set to optimum. Otherwise, the system fails to detect some errors, detects false errors, and report duplicate errors. The image processing module detects errors with a percentage of 100% when the brightness level is between -50 to 50 on a scale of -100 to 100 (where 0 is the normal lighting).

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I hereby affirm that this work was created exclusively by myself and that no other sources and auxiliary means other than the ones stated were used. All material or text which was extracted literally or analogously from other published work is explicitly stated.

Stuttgart, September 7, 2011

(Eid Badr)