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Lars André Langøyli Giske

Robotic Cleaning of Fish Processing Facilities

Virtual tools, hygienic design and prototyping

Doctoral thesis

NTNU
Norwegian University of Science and Technology
Thesis for the Degree of
Philosophiae Doctor
Faculty of Engineering
Department of Ocean Operations and Civil
Engineering

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Abstract

Fish and seafood products are among the most valuable resources when considering ways in which to address the need for sustainable food sources in the future. However, any increase in fish processing production must be implemented in an environmentally sustainable way. The cleaning of fish processing plants and equipment the equipment used in such facilities has been identified as an area in which research has the potential to make significant contributions to the reduction of environmental impact, both in terms of the utilization of chemicals during cleaning and the general water consumption that occurs in the processing of fish and the cleaning of fish processing equipment and facilities.

Currently, the most commonly used cleaning practices in the fish processing industry are based on manual operations, which are both subject to human error and unstable. Furthermore, the cleaning of fish processing plants is a demanding manual operation that is characterized by repetitive and stressful tasks. In addition, cleaning fish processing plants is also very costly; however, it is a necessary final step in the daily process of such facilities to ensure food safety. The automatization of such processes has been the go-to approach to solving the challenges faced by such facilities and thus increasing profits in the Norwegian aquaculture industry.

The main objective of this thesis is to determine how fish processing plants may be cleaned more efficiently. The research for this thesis was conducted in the context of an industrial research project intended to develop a robotic cleaning system for fish processing plants. It is predicted that a robotic cleaning system could reduce both the risk of bacterial contamination and costs related to cleaning. Conventional industrial robots have proven to be well-suited to performing repetitive and demanding tasks. Nonetheless, at the moment, no solution exists for the robotic cleaning of fish processing plants. A major challenge for robots to perform cleaning is conventional industrial robots' tolerance and ability to adapt to the humid and challenging environments found in fish processing plants, especially during cleaning.

Other challenges arise when considering the commissioning, installation, and industrial performance of complex products such as robotic cleaning systems. Very few new fish processing plants are built each year in Norway; thus, a viable robotic cleaning system concept must be able to be retrofitted into existing plants. Fish processing plants have complex layouts; in addition, spatial information concerning such facilities is often lacking. Furthermore, they run almost continuously. These factors make installation and commissioning time a crucial part of achieving industrial performance and implementation of a robotic cleaning concept.

Developing a robotic cleaning solution requires product development efforts. Product development is important when attempting to obtain competitive advantages, and this research explores how product development is approached in the Norwegian aquaculture industry. In addition, this thesis explores modern virtual prototyping tools and how they can be used to solve some of the challenges related to product development and industrial performance in this industry. Specifically, 3D scanning is proposed as a method for capturing spatial data concerning fish processing plants to aid in the planning and installation of the proposed robotic cleaning system. Furthermore, 3D simulation of robots (e.g. offline programming) provides information about the systems function and performance at early stages of product development and utilized to speed up the product development process and to identify potential errors, improvements and applications with regard to the robotic cleaning system. The project demonstrates that 3D scanning and simulation in combination may well prove key in achieving an acceptable level of industrial performance for a robotic cleaning system.

The results of the research work are two distinct, full-scale robotic cleaning prototypes, which are evaluated by deliberately contaminating fish processing equipment with bacteria, after which the equipment is cleaned. The residual bacterial levels on the equipment are measured to indicate cleaning effectiveness. For the cleaning process, the robotic prototypes are programmed according to best practices in industrial cleaning. Both tests show that robotic cleaning reduces the bacteria count significantly, and the second prototype cleaning system is found to perform as well as a human operator with 15 years of cleaning experience in fish processing plants.

The first full-scale prototype consisted of a UR10 industrial robot with two auxiliary axes to increase the size of the working envelope. Even though it was found that such a solution is inadequate in terms of reach and functionality, this prototype proved that robotic cleaning is a plausible means of improving cleaning efficiency. The first full-scale prototype provided valuable insights, which enabled the development of a second, more industrialized prototype.

The second prototype robotic cleaning system for fish processing plants was developed and tested in a close-to-real-life lab environment. The system consists of a custom-made linear horizontal rail and trolley, together with a custom-made manipulator specifically designed for the robotic cleaning of fish processing lines. All components are made to withstand the harsh environments in which they will operate, which are characterized by the use of chemicals and high levels of humidity, while also adhering to hygienic design requirements. The design of the system enables the robotic arm to have a long reach while keeping the system's footprint and weight relatively low when compared to conventional robotic arms. Furthermore, the custom-built robotic cleaning system is designed to be adapted to the various spatial layouts to be found in fish processing plants.

Hygienic design principles were considered during all phases of the product development process to ensure that the robotic cleaning system does not impose any additional threats to food safety in fish processing plants. In addition, hygienic design insights concerning the Norwegian aquaculture industry are evaluated and expanded upon in relation to existing theory regarding hygienic design as well as design for cleaning practices.

It is demonstrated that it is possible to clean fish processing plants through the implementation of robot(s) by utilizing modern virtual prototyping tools and that such an approach is likely to produce results that are equal to or superior to those obtained using traditional cleaning methods. It is also noted that hygienic design plays an important role in enabling robotic cleaning in fish processing plants. Robotic cleaning of fish processing plants has the potential to reduce both production downtime due to cleaning and the need for manual labor, improve the overall hygiene of many processes, and eliminate tasks involving heavy manual workloads.

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List of Abbreviations

ATP	Adenosine triphosphate
CAD	Computer-aided design
CFU	Colony-forming units
DES	Discrete event simulation
DOF	Degree of freedom
EHEDG	European Hygienic Engineering Design Group
FPE	Fish processing equipment
FPP	Fish processing plant
HSE	Health, safety, and environment
LoA	Level of accuracy
LoD	Level of development
LoR	Level of recognizability
NAI	Norwegian Aquaculture Industry
PD	Product development
PLC	Programmable logic controller
TRL	Technology readiness level
VFL	Virtual factory layout

1 Introduction

1.1 Background and Motivation

The Norwegian aquaculture industry (NAI) is large and generates a yearly revenue of over 6 billion EUR (Statistics Norway, 2018). Modern fish processing plants (FPPs), both those that are located on onshore and aboard fishing vessels, compete on the global market for fish and seafood. Many problems arise in catching/harvesting, processing, and distributing fish and seafood; however, these problems also represent opportunities. The global market for fish and seafood is growing rapidly; as a result, the number of fish farms and customer demands are also increasing. The global fishing industry is expected to expand in the upcoming years to satisfy the demand for high-quality protein due to the anticipated population growth globally (World Bank, 2013). Fish processing plants must be expanded and automated to handle higher volumes, improve the quality of their product, and enhance efficiency (in terms of using as much of the fish as possible) to satisfy the needs of the best-paying customers. In this thesis, fish processing is regarded as referring primarily to post-catch or post-harvest operations such as stunning, killing, chilling, bleeding, sorting, grading, gutting, de-skinning, filleting, and trimming, but it may also refer to smoking, pickling, freezing, and packaging. Seafood products are highly perishable and require immediate processing to ensure the highest quality.

The fish processing industry continues to be fast growing, particularly the aquaculture of salmon and trout, which has grown extremely rapidly in Norway, Scotland, and Chile over the past decade. In addition, aquaculture in general has come to account for an increasing portion of the total amount of fish processed across continents, and several species of fish are now farmed (FAO Fisheries and Aquaculture Department, 2016); furthermore, countries such as Russia, Australia, the Faroe Islands, and Iceland are increasing their production (Berge, 2017) significantly, thus making the industry increasingly more global. Although few new factories are built in Norway each year, new factories are continually being built in many countries, and new processing equipment and technologies have been swiftly developed and implemented in both new and existing processing plants over the last decade.

The rate of innovation has been very high, and, simultaneously, many new technologies related to industrial applications and solutions for the fishing process industry have emerged. The complexity of innovations has also been steadily increasing, and there are increasing numbers of automated and robotized products with sophisticated accessories such as vision technology, sensors, and robotics. Environmental issues associated with fish production are also becoming increasingly important. Due to high labor costs in Norway, labor constitutes a high portion of the total production costs in this industry. Increasing the degree of automation and flexibility is considered crucial to make the seafood sector in Norway more competitive in the future, and this will require research focused on technological developments intended to improve manufacturing efficiency (Fisheries and Aquaculture Industry Association, 2012).

The Norwegian Government's ambition is for Norway to become one of the world’s leading seafood nations (Norwegian Ministry of Fisheries and Coastal Affairs, 2013a, 2013b). Several measures are needed for this goal to come to fruition. Most of the

Norwegian salmon is filleted (or processed further than slaughtering and gutting) in receiving countries, and not in Norway. The fish obtains a much higher quality with pre-rigor fileting, e.g., fileting straight after slaughter. However, due to the high costs and low profitability of processing in Norway, the fish is sent whole to low-cost countries, which does the fileting. By implementing more automation in the NAI, it is suspected that the overall production costs could go down due to lower processing costs, and aid in facilitating more processing in Norway and increasing profitability. An added benefit would be the possibility of emerging industries that utilize the residual raw material to produce, e.g., marine health products (Norwegian Ministry of Fisheries and Coastal Affairs, 2013b). Profitable processing of seafood in Norway requires a high degree of automation of the process, both the processing of fish itself and the cleaning- and maintenance processes. Such automation will contribute to reduced production costs. More automated processing plants with a focus on quality and product development will lead to an increased degree of processing in the fish industry (Digre, Mathiassen, Standal, & Grimsmo, 2014). The same report also states that hygienic design is a relevant research need in this respect.

There are several challenges obstructing the further growth of this industry; one challenge in terms of achieving greater productivity and lower resource consumption is developing less resource-demanding food processing equipment (Karlsson & Luttropp, 2006; Winther et al., 2009). The processes mentioned previously are directly related to processing a fish from raw material into finished product.

Other challenges are related to sustainability. The Norwegian fishing industry is today constituted of companies that export raw material or semi-processed fish for further processing in other countries, often combined with re-import of finished product to Norway or Europe. If one succeeds in creating more profitable and higher quality production in Norway due to new technology, the whole industry will experience the impact. Large volumes of fish are today sent frozen to China for thawing, processing, and freezing and then shipped back to EU or even back to Norway. Sintef have made estimations of the potential reduction of carbon footprint in their report "Energy usage and climate emissions by export of Norwegian seafood"(2009). It states that through replacement of today's practice of exporting whole, gutted salmon for filet-processing in foreign countries, with equivalent processing (e.g., filleting) in Norway, will reduce the carbon footprint by 12% and 10% for land-based transport and air-based transport, respectively (Ellingsen et al., 2009). The same report concludes that transport, in general, constitutes the bulk of emissions related to the export of Norwegian seafood. The trend is currently negative; from 2010 to 2018, the percentage of exported unprocessed fish from Norway has increased from 67% to 72% (Norwegian Seafood Counsil, 2019). This trend is only possible to reverse through the automation of processes. Moreover, "Research shows that processing equipment design has a significant effect on the environmental impact of the salmonid processing value chain. Based on analysis of existing production technology, several environmental equipment design-related factors were identified, including (a) Total utilization of raw material for human consumption; (b) increase in the fraction of raw material used in main product (c) reduction of washing agents, and disinfectants and (d) water consumption during processing." (Bar, 2015, p. v).

The cleaning of fish processing plants is typically overlooked when discussing fish processing, but it is absolutely essential in ensuring food safety and high-quality products (Christi, 2014; Windsor & Tatterson, 2001). The cleaning of fish processing plants and the equipment therein is very resource-demanding, as thorough cleaning is important to ensure food safety. One challenge with regard to food safety is the presence and the potential contamination of fish from the human pathogenic bacterium *Listeria monocytogenes* during production. This bacterium may pose a health risk for consumers, particularly those with impaired immune system functionality (Rees, Doyle, & Taylor, 2017).

Today, this bacterium is kept in check in fish processing plants by means of rigorous cleaning procedures. However, the cleaning process is unstable and a point of uncertainty in the fish processing value chain, and it is believed that robots could take over this manual operation in the future. In her PhD thesis, Eirin Bar found that the NAI in general places little emphasis on sustainability and identified cleaning as the third item on a list of measures that could be taken to minimize the environmental impact (Bar, 2015). Specifically, reducing the need for washing agents and disinfectants and minimizing water consumption are crucial of importance. Cleaning is also explicitly identified as one of the key areas to focus on to increase the profitability of the NAI in a report provided by Sintef (Digre et al., 2014). Specifically, this report identifies fully automated cleaning stations, cleaning robots for production facilities, and hygienic designs for all machines as potential innovations. The Norwegian government has identified the automation of fish processing as the preferred strategy by which to increase the competitiveness of the Norwegian fish food production market globally, predominantly by reducing the use of manual labor through automation (FHL (Fisheries and Aquaculture Industry Association), 2013; Fisheries and Aquaculture Industry Association, 2012; Norwegian Ministry of Fisheries and Coastal Affairs, 2013b; The Research Counsil of Norway, 2012). Increased use of robots and automation of processing tasks are global trends in the contemporary food industry (Chua, Ilschner, & Caldwell, 2003), but existing solutions are often highly dependent on manual labor to aid automated processes (Bondø et al., 2011).

Optimar AS (Optimar AS, 2019), a Norwegian company producing machines and equipment for the fishing industry both on- and off-shore, has recognized the cleaning problem and realized that automation may be the key to solving it. Together with NTNU,[1] Nofima,[2] and the Research Council of Norway, Optimar has launched a project with the goal of developing a robotic cleaning solution suitable for industrial contexts for their customers that can clean 50% of the processing lines in fish processing plants, for instance by doing all cleaning at the slaughtering portion of a processing line, and thus replacing several cleaners. The area and the number of cleaners will be determined based on each FPP's capacity (and consequently size and layout), which may range between slaughtering 30 to 270 tons of fish per hour per 8-hour shift (Norsk Fiskerinæring, 2018). In this context, the implementation of such a system and the need for it to demonstrate industrial levels of performance mean that it must adhere to the hygienic design standards that exist in the industry and overcome the difficulties associated with the implementation of such a system. However, the potential for innovation in these factories is still high, and the business remains profitable and fast-growing. This development will likely continue in the upcoming years (FAO Food and Agriculture Organization of the United Nations, 2016). Within the context of the fish processing industry, efficient, safe, clean, innovative, upgradeable, and environmentally

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[1] Norwegian University of Science and Technology (Norwegian University of Science and Technology, 2019)

[2] Norwegian Institute of Food, Fisheries and Aquaculture Research (Nofima AS, 2019)

friendly fish processing will be extremely important; however, satisfying these requirements will require effective product development strategies and methods.

1.2 Problem Description

A robotic cleaning solution intended to address several of the challenges associated with the manual cleaning of fish processing equipment (FPE) is. Robots are ideal for repetitive, unergonomic, and hazardous tasks and those in which health, safety, and environment (HSE) requirements are an issue for manual operators (International Federation of Robotics, 2018). To a large degree, the research interests of scholars have focused on the application of robots in traditional manufacturing disciplines such as assembly and welding; in addition, many researchers have focused on tools and techniques with which to expand the working capabilities and enhance the performance of such robots, such as computer vision, force/torque control measures, and machining and welding tools. Many standard existing robot models have simply been customized for use in the food industry, as opposed to being developed specifically for it, which makes them less than ideal for use in the food industry (Masey, Gray, Dodd, & Caldwell, 2010).

The existing literature has addressed neither the cleaning of processing plants nor tools for such applications. However, in her thesis, which focuses on food processing equipment design for a sustainable salmonid fish industry, Bar (2015) identifies potential approaches for enhancing the sustainability of fish processing: 1) the implementation of fully automated washing stations, 2) the automated washing of production facilities, and 3) hygienic design of equipment, machinery, and processing plants.

Financial justification for the installation of a robotic system is typically based on the reduction of labor costs. According to Masey et al. (2010), the bulk of manual labor in a food production line is concentrated in packaging and assembly operations, which require high throughput, higher levels of hygiene, and greater flexibility. However, today, the cleaning of FPPs is a repetitive manual task that is conducted in harsh working environments due to due to the fact that both water and chemicals are sprayed onto equipment which generates a spray fog; in addition, such work requires a high degree of flexibility on the part of cleaning staff. It is very common to clean FPPs at night, which drives costs up. The spray hoses are heavy and must be dragged manually, and the operation is thus physically demanding. The turnover in terms of cleaning staff is high, both in dedicated cleaning companies and at those FPPs that directly employ cleaners. Cleaning operations are unstable, subject to human errors, and time-consuming and costly (Løvdal, Giske, Bjørlykhaug, Eri, & Mork, 2017).

The above paragraphs presented only an overview of the problems associated with cleaning in FPPs; additional information concerning such cleaning is presented in Chapter 3. The cleaning problem is, however, only one side of the equation. Challenges arise when considering how a robotic cleaning solution may be implemented in the industry fish processing industry; such challenges must be considered when attempting to develop a solution to the work and costs involved in cleaning and addressed in order to contribute to the future development of this industry.

1.2.1 Industrial Implementation and Performace

Several challenges are associated with the industrial implementation and performance of a robotic cleaning system beyond the technical details concerning the system itself, such as those associated with the design process of the manipulator and its control system. Due to the reasons presented in the following subsections, smart methods of installation and implementation will be essential to make a robotic cleaning system commercially available.

As a result of the varying production capacities of Norwegian FPPs, which range from 30 to 270 tons of produced fish per processing shift (Norsk Fiskerinæring, 2018), every processing plant is unique, as can be seen in Figure 1.1 through Figure 1.2. The reader is also referred to see Figure A.7 through Figure A.12 on page 88 for additional examples of slaughtering lines in FPPs. They are often built and modified incrementally, and prototypes of new technologies are often found as part of their running processing lines. As a result, and due to the fact that innovative approaches to solving issues in the processing lines are implemented continuously, the layout and design of and the equipment used in each factory lead to each plant becoming a unique installation. In addition, modern FPPs are built incrementally, they face challenges regarding obtaining and maintain accurate spatial information. The documentation concerning an FPP's layout often contains outdated or incorrect information; alternatively, it may not even contain relevant information, such as that on failures or changes that have been made to an FPP during its lifetime. During the installation of equipment both during the installation of new processing equipment and when retrofitting, small changes occur on site that are usually not fed back into the documentation concerning the layout. This is also the case for some infrastructure, as doors, beams, pillars, and the like are often not placed according to the intended layout. Heating, ventilation, and air-conditioning (HVAC) systems are rarely modeled in 3D or in the same 3D layout as that detailing the placement of equipment, leading to uncertainty as their placement. This is in stark contrast to the contexts in which conventional industrial robots are used, in which factory layouts are often planned around robots and machinery.

In addition to the problems related to spatial information, there is the difficulty posed by the spatial layout of a facility, which differs widely from FPP to FPP. Consider Figure 1.1 and Figure 1.2 and notice the differences in ceiling height, layout, and equipment placement. This variety creates a need for a flexible solution to a robotic cleaning system that can be tailored through modularization to each FPP. The space available on floors, in ceilings, and in the space around equipment is generally limited, meaning that a robotic cleaning solution should also have a small footprint and a slender build. Fish processing plants are also often quite large in terms of volume, so a solution must have a long reach (> 2m). For additional images that display a fraction of the variances which may occur in FPPs, please consult *Pictures of different FPPs* on page 88.

Figure 1.1 Slaughter line at FPP 1.

Figure 1.2 Slaughter line at FPP 2.

The proposed robotic system is intended to clean the slaughtering line section of an FPP, examples of which are presented in FiguresFigure 1.1 throughFigure 1.2. These images illustrate the complex geometries and diverse layouts that are present in different FPPs. However, it should be noted that the above images represent only a few FPPs, and there are as many different layouts as there are FPPs. Consider the amounts of fish and blood shown in Figure A.8 (page 89) and Figure 1.2 to obtain an impression of the amounts of fish that are processed and what needs to be cleaned after processing.

In general, the fish processing industry runs on 24/7 basis, and stops in operations beyond mandatory holidays are rare and usually planned far in advance. Fish processing plants work five days a week throughout most of the year, typically with two processing shifts and one cleaning shift. This means that their fish processing lines run continuously, and every stop for engineering activities, installation and commissioning, and service and upgrading is extremely expensive and undesirable from a processer’s point of view. In addition, as discussed previously, each factory has a unique layout. To reduce deployment time, it is important that new equipment functions correctly when it is installed. Each hour spent not producing at full capacity is very costly for FPPs, as, on average, in 2016, FPPs generated a profit of 16.7 NOK per kilogram of fish produced (Fiskeridirektoratet, 2016a). In 2016, 1.2 million tons of salmon and 0.87 tons of rainbow trout (Fiskeridirektoratet, 2016b), with a value of 60 billion NOK and 3.7 billion NOK, respectively, were sold. This illustrates the importance of keeping production at full capacity for as much time as possible.

The installation of complex equipment is thus difficult, as it usually requires a stop in production and gives rise to a need to clean after installation. This is not a major issue when installing relatively simple equipment such as a conveyor, but the task becomes more demanding when it comes to the installation and commissioning of a complex equipment such as a robotic cleaning system. In addition, the installation of equipment in FPPs introduces the risk of bacterial contamination, which increases with time taken for installation (Moerman & Wouters, 2016b, 2016a).

One may well ask whether a viable solution could be incorporating the design of a robotic cleaning system in the planning phase of new fish processing facilities. After consulting both other Optimar employees and the owners of several FPPs, the answer was found, unsurprisingly, to be yes. However, from the perspective of a supplier responsible for the installation of robotic cleaning systems and the technology used in them, the market would not be sufficiently large. In Norway, very few new FPPs are built each year, and thus both the technological features of and the implementation/business model for a robotic cleaning system must take into account the retrofitting of such a system into existing fish processing facilities.

Together, these challenges give rise to a substantial risk of failure when attempting to install, commission and implement complex equipment or systems. This is undesirable in FPPs both from an operations and financial perspective and from a bacteriological perspective.

The existing literature has not explored the application of robots for cleaning FPPs. There is also no literature available concerning how such a robotic system could be installed, commissioned, and operated. This thesis addresses these gaps by investigating the specifications that would be required of a robot to be used for such applications and examining the use of modern design tools to achieve rapid installation and commissioning times.

1.3 Scope of Work, Research Questions and Research Objectives

In light of the previously outlined problem formulation, tree areas are identified as the main topics investigated in this thesis: The first is the development of a robotic cleaning system. Secondly, virtual factory layouts and prototyping environments, which in essence, explores ways by which such a system could attain industrial levels of performance. Lastly, hygienic design is identified as a relevant topic. The scope is shown below in Figure 1.3.

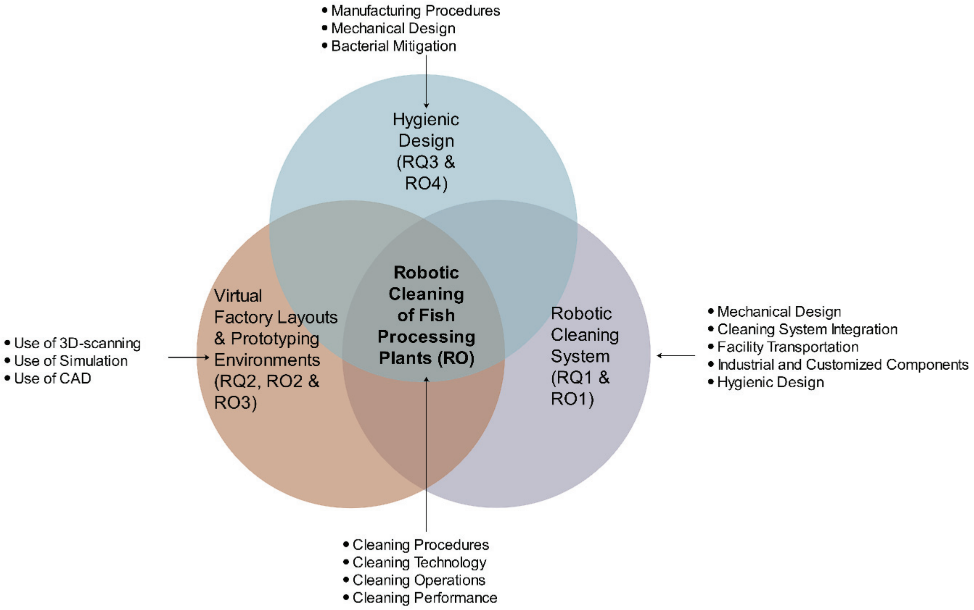

Figure 1.3 Scope of this work.

The overall research objective (RO) is as follows:

Exploration of how fish processing plants may be cleaned more effectively through the use of robotics

The term "effectively" is, in this case, aimed toward achieving sufficient cleaning quality. Sufficient quality means that the desired outcome is a clean fish processing plant, with minimum bacterial contamination threats. In addition to producing the desired cleaning result, it should improve working conditions, decrease cleaning time, lead to a more stable cleaning process, and increase the possibilities of logging and control of the cleaning.

A breakdown of this overall research objective yields four separate ROs:

RO1. The proposal of a robotic cleaning system for fish processing plants that satisfies the requirements identified in this work for such systems;
RO2. The proposal of a method for enabling retrofit installations of said robotic cleaning system;
RO3. The proposal of a method that enables rapid installation and commission of such a system; and

RO4. The proposal of hygienic design principles for fish processing equipment.

To investigate these objectives, tree Research Questions (RQs) are proposed:

RQ1. How can a robotic cleaning system be designed such that it will outperform the manual approach to cleaning currently used in most FPPs?
RQ2. How can modern design tools be utilized to enable rapid installation and commission as well as industrial performance on the part of novel FPE?
RQ3. What are the hygienic design principles for FPE?

Six published research articles, included in the Appended Papers section, investigates these questions. Their relations to the tree overall research topics are presented below in Figure 1.4.

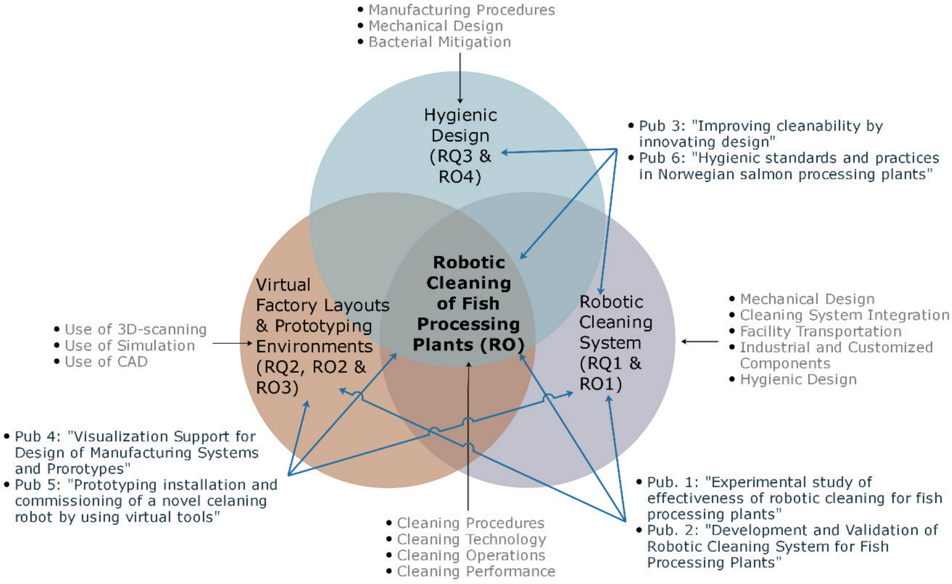

Figure 1.4 Each paper's correlation to the Scope of Work.

1.3.1 Delimitations

Automation and control systems for the robotic cleaning system are presented in this thesis to provide a better overview of the proposed systems. However, they are not part of the study conducted in this work. Also, this thesis neither goes into the details of fish processing or fish processing plant hygiene nor the microbiological aspect of cleaning (beyond a presentation of cleaning tests and their results).

Simulations of robot and manipulator movements were performed during development in this study. The thesis does not address the programming of such robot and manipulator movements. Instead, the thesis focuses on their use and impact on product development and prototyping activities and processes. A parallel PhD thesis by Emil Bjørlykhaug (2018) covers the programming facet of these simulation activities. The aspects towards achieving an intelligent robot with real-time decision making and adoption capabilities, as opposed to a “dumb machine” which receives instructions, are consequently not a part of this research work. Some future perspectives are mentioned and briefly discussed, however.

The section of this thesis focused on hygienic design and designing for cleaning focuses on the physical design of parts, products, systems, or even entire factories to mitigate bacterial risk. This emphasis on mitigating bacterial contamination is implicit within the design of the robotic cleaning system presented in this thesis. However, this work also makes contributions to this field beyond this system.

1.4 Publications

Each of the publications that this thesis is based on, along with each author's contribution, is presented in the following list:

1. Giske, L. A. L., Bjørlykhaug, E., Løvdal, T., & Mork, O. J. (2019). Experimental study of effectiveness of robotic cleaning for fish-processing plants. *Food Control.* (Lars Andre Langøyli Giske, Bjørlykhaug, Løvdal, & Mork, 2019)
   This manuscript was developed as a collaborative venture between L. A. Giske and E. Bjørlykhaug, with both authors making equal contributions. This is a continuation of Paper 2, in which the contributions from the first robot system are presented; the contributions made to the development of the second robot system follow. Bjørlykhaug proposed the robotic manipulator, built the control system, and performed the simulations and programming of the robot trajectories. The robotic system was built in collaboration between E. Bjørlykhaug, L. A. Giske, and an industry partner. In addition to enabling the testing, L. A. Giske designed the laboratory environment and facilitated the building of the laboratory environment. Giske also designed both the system around the manipulator, including the custom horizontal rail and trolley, and the cleaning system of the manipulator. T. Løvdal designed the microbiological experiment and conducted it in collaboration with L. A. Giske. All of the co-authors assisted in improving the manuscript.
2. E. Bjørlykhaug, L. A. Giske, T. Løvdal, O. J. Mork and O. Egeland. Development and Validation of Robotic Cleaning System for Fish Processing Plants. *IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*. 2017 (Bjorlykhaug, Giske, Lovdal, Mork, & Egeland, 2017)
   The work performed for this publication was mainly divided between E. Bjørlykhaug and L. A. Giske. Initial designs were developed by E. Bjørlykhaug, L. A. Giske, and O. J. Mork. E. Bjørlykhaug performed the simulations of the robotic system, while E. Bjørlykhaug and L. A. Giske built and programmed the prototype robotic system. T. Løvdal developed the microbiological experiment and performed the experiment in collaboration with E. Bjørlykhaug and L. A. Giske. E. Bjørlykhaug was the main author of the manuscript. All of the co-authors assisted in improving the manuscript.
3. Giske, L. A. L., Mork, O. J., & Bjoerlykhaug, E. (2017). Improving Cleanability by Innovating Design. *Journal of Hygienic Engineering and Design* (Lars Andre Langoeyli Giske, Mork, & Bjoerlykhaug, 2017)
   L. A. L. Giske brought forth several design alternatives for different equipment for improving hygienic design and tested the resulting designs in fish processing plants. All of the co-authors assisted in improving the manuscript.
4. Giske, L. A. L., Benjaminsen, T., Mork, O. J., & Løvdal, T. (2019). Visualization Support for Design of Manufacturing Systems and Prototypes – Lessons Learned from Two Case Studies. *Procedia CIRP* (Lars Andre Langøyli Giske, Benjaminsen, Mork, & Løvdal, 2019)
   T. Benjaminsen and L. A. L. Giske performed the 3D scanning together and shared the work of developing the models of both lab and processing facilities based on the 3D scans. O. J. Mork contributed to the industrial use case, while T. Løvdal provided a

microbiological perspective. L. Giske was the main author of this manuscript, and all of the co-authors assisted in improving it.

5. Giske, L. A. L., Benjaminsen, T., & Mork, O. J. (2019). Prototyping installation and commissioning of a novel cleaning robot by using virtual tools – lessons learned. *Procedia CIRP* (Lars Andre Langøyli Giske, Benjaminsen, & Mork, 2019)
   L. A. L. Giske interpreted the simulation results from the research project conducted with Optimar and adopted the findings for the framework and industry setting presented in this study. The design errors discovered during the simulation were addressed by L. A. L. Giske. All of the co-authors assisted in improving the manuscript. E. Bjørlykhaug performed the actual simulation but did not participate in the writing of the manuscript.
6. Løvdal, T., Giske, L. A. L., Bjørlykhaug, E., Eri, I. B., & Mork, O. J. (2017). HYGIENIC STANDARDS AND PRACTICES IN NORWEGIAN SALMON PROCESSING PLANTS. *Journal of Hygienic Engineering and Design* (Løvdal et al., 2017)
   L. A. L. Giske provided relevant information concerning industry standards and practices and also facilitated access to industry facilities, in addition to making contributions during the writing of the manuscript. T. Løvdal performed the microbiological experiments together with I. B. Eri. O. J. Mork contributed to writing the manuscript.

1.5 Contributions

The main contributions of this thesis are the development and prototyping of robotic systems for the cleaning of fish processing lines and plants, in addition to the exploration and application of designs and virtual tools for enabling the efficient implementation of robotic systems in FPPs. The thesis verifies that the robotic system can deliver satisfactory industrial cleaning results and demonstrates how the system could be implemented in the industry. There is no existing literature that elaborates on the design of robotic systems for the cleaning of FPPs, demonstrates how such a system could work, or documents the effectiveness of robotic cleaning systems for FPPs, nor do such solutions exist in the fish processing industry itself at the time of writing.

1. Two full-scale concepts and prototypes of robotic systems for the cleaning of fish processing plants have been implemented on a prototype level. They have been tested thoroughly and both technologically and microbiologically verified. For the second prototype, a near-industrial robotic system was developed. It is composed of a custom-built 6 degree of freedom (DOF) robotic manipulator in combination with a custom-designed linear rail. The second robotic system, Prototype 2, was developed, implemented, and tested in a laboratory environment established for the task. In this laboratory, back-to-back tests with both manual and robotic cleaning were performed to evaluate the effectiveness of the cleaning system. The robot cleaning systems interfaces with standard industrial cleaning equipment and are evaluated in an industrial laboratory context. The findings of the verification test show that, should the robotic system be implemented in FPPs, this solution will greatly improve cleaning performance, cleaning procedures, and cleaning operations and eliminate demanding manual cleaning operations. In addition, investigating the use of the robotic system in practice is likely to provide new insights into the applications for which robots can be used in the food industry. This point is related to the *robotic cleaning system* section of the scope of work depicted in Figure 1.3.
2. In addition, this work also explores the use of 3D scanning as a tool for use with 3D robotic simulations and how it can be utilized to improve the installation and

commissioning performance of equipment and systems into FPPs. The use and benefits of 3D scanning in complex retrofitting engineering projects wherein time and cost are critical factors are also demonstrated. Two 3D scanning scenarios are evaluated using a novel framework focused on the requirements of virtual factory layouts (Eriksson, Sedelius, Berglund, & Johansson, 2018). New knowledge concerning how this technology may be utilized in the NAI, both to obtain direct benefits during the planning phase and future benefits through changing working processes to exploit the possibilities offered by this technology, is presented.

3. Based on an investigation into the offline programming of robots in 3D simulations (robot simulations), insights are presented into how the offline programming of robots supports the development, installation, and commissioning of novel automated technologies, such as a robotic cleaning system. It is discovered that, through simulation, it is possible to reduce installation and commissioning times, as well as product development times. These savings in time impacts the industry in two areas; first, it may reduce unwanted FPP downtime. Second, simulation may aid in bacterial mitigation through reducing the time required for the installation and implementation of equipment and machines. The body of knowledge regarding simulation is expanded through the use of simulation in prototyping activities. Points 2 and 3 of this list are presented in relation to the themes of *virtual factory layout and prototype environments* in Figure 1.3.
4. Further advancements in hygienic design, as well as design for cleaning in the aquaculture industry, are presented through concepts and prototypes. Relevant theories and current practices are presented and expanded upon based on real-life examples of how design challenges are solved in the NAI. The hygienic design perspectives are related to the *hygienic design* aspect of the scope of this work depicted in Figure 1.3.

Together, these contributions add to the knowledge on how the *cleaning of fish processing plants* (see Figure 1.3) may be changed to shift towards improved industrial performance. In addition, instead of adopting the traditional method of developing products in the context of the industry, this research focuses on the role of processing equipment within the environmental and business conditions in which seafood production is conducted. Emphasis is placed on considering these conditions into the product development processes by integrating the biological, technological, industrial performance, and design perspectives.

When compared to the traditional technology-focused methodology adopted in the aquaculture industry, this thesis' scope in terms of product development methods is expanded by the incorporation of the three main knowledge domains that are present in FPPs: fish processing performance, technology, and microbiology. The thesis encompasses both the design perspective and the manufacturing operations perspective of FPE, in addition to the perspective concerning the use of FPE. In this regard, this work can be considered a noteworthy contribution to the existing scientific body of knowledge on efficient and sustainable fish processing.

1.6 Thesis Outline

The remainder of this thesis is structured as follows:

- Chapter 2 describes various theories that are relevant to the work conducted in this thesis. These concepts include product development, prototyping, and tools used for prototyping, such as simulation and 3D scanning. Relevant theory on hygienic design and design for cleaning is also presented.

- Since the current state of the art in the field of industrial cleaning is determined based on both theory and the findings in this thesis, this is presented on its own in Chapter 3.
- The development of the robotic systems investigated in this thesis and the lab environment in which they were tested is presented in Chapter 4. This chapter includes the mechanical designs of the robotic systems and their interfaces to industrial infrastructure. The requirements for a robotic cleaning system are also presented in this chapter, and it is thus also part of the results.
- Chapter 5 presents the results of the work that was conducted for this thesis.
- Chapter 6 serves as the conclusion and presents recommendations for further work.
- Finally, the Appendix includes the mechanical design results of the two prototypes and a detailed comparison between them in Table A.1.
- The Appended Papers includes the publications that this thesis was based on.

2 Theory

This chapter presents relevant theory, starting with product development (PD) and prototyping. Both these activities permeate the work done in this thesis, along with hygienic design considerations, which are important when designing machines and equipment for the food industry. Theory regarding the use of 3D scanning and simulation as tools for PD and prototyping is presented. Finally, theory regarding the use of robots in the food industry is presented. Some of these theories is also covered in other parts of this thesis.

2.1 Product Development

Product development is characterized by transforming a market opportunity into a product that meets customers' needs while also matching the strategic goals of a company; this is done through a network of interacting activities (Browning & Ramasesh, 2007; Kennedy, 2003; Krishnan & Ulrich, 2001). Product development is considered to be a means by which companies can obtain the competitive advantages required to survive in fast-paced environments (Ahmadi, Roemer, & Wang, 2001; Browning & Ramasesh, 2007) and has been influenced by a need for increased effectiveness and efficiency, which in this context is seen as meaning more rapid introduction of superior products that cost less to produce to the market (Browning, Deyst, Eppinger, & Whitney, 2002; Eppinger, Nukala, & Whitney, 1997; Eppinger, Whitney, Smith, & Gebala, 1994; Fiore, 2005).

Companies that produce FPE often define product requirements in close collaboration with their customers as part of the PD process (Bar, 2015), but a strong dependence on the acceptance of a product by a buyer may lead to a manufacturing becoming reluctant to investigate solutions that are perceived as less relevant to the customer. Product development efforts are largely focused on technology. There are forces emerging that should encourage the original equipment manufacturers (OEMs) of the fish processing industry to reconsider their PD process with regard to increasing its effectiveness. Some of these forces are, in no particular order, increasing international competition, rapidly changing technology (and new applications of existing technology), and increasingly fragmented markets (with new fish species being farmed or evaluated for farming). This state of affairs is not unlike what Wheelwright and Clark discovered with regard to the automotive industry, which consider PD as being crucial to organizational survival in high-pressure environments. In their book *Revolutionizing Product Development: Quantum Leaps in Speed, Efficiency and Quality*, the authors identified three "development imperatives" for competing companies: quality (including reliability, functionality, and customer satisfaction), cost or efficiency (vehicle/product and PD costs), and time, here meaning the time from concept to market (Wheelwright & Clark, 1992).

These same imperatives have been used by other authors as measures of the performance of PD processes, such as Clark and Fujimoto (1991) or Smith and Reinertsen (1997). Many of these authors have agreed that organizations that wish to be successful in terms of PD must excel in all three areas.

Ulrich and Eppinger (2015) proposed a generic PD process, which is presented in Figure 2.1 below, followed by a brief explanation of the various subprocesses that constitute the process as a whole.

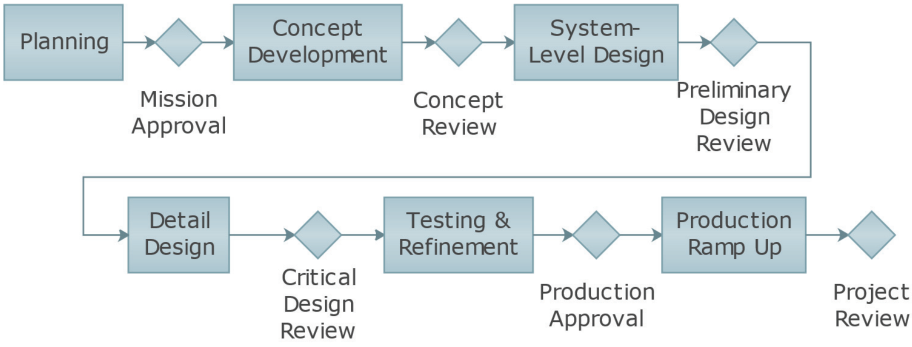

Figure 2.1 Generic PD process (from (Ulrich & Eppinger, 2015)).

Planning: Planning often occurs prior to project approval and the beginning of the actual PD process. Opportunities are identified based on corporate strategy, and the planning phase includes assessment of technological developments and market objectives. The project mission statement, which specifies the target market for a product, business goals, key assumptions, and the related constraints, is the output of this phase.

Concept Development: In this phase, the needs of the target market are identified, alternative product concepts are generated and evaluated, and, often, one or several concepts are selected for further development and testing. The output of this phase is thus one or more concepts, where a "concept is a description of the form, function, and features of a product and is usually accompanied by a set of specifications, an analysis of competitive products, and an economic justification of the project."

System-level Design: Initial plans for the production system and final assembly are usually defined in the system-level design phase. These are formulated based on the definition of the product architecture, decompositions of the system into subsystems and components, preliminary designs of key components, and allocation of responsibility with regard to detailed design (internally and externally). The output typically includes a geometric layout of the product, a preliminary process flow diagram for the final assembly process, and functional specifications for each of the product's subsystems.

Detail Design: During the detail design phase, the geometry, materials, and tolerances of all of the unique parts should be completely specified, and all parts that will need to be purchased from suppliers should be identified. Process plans and tooling for parts that must be fabricated are decided and designed. *Control documentation* (e.g. drawings/computer files describing the geometry of each part and its production tooling, the specifications of purchased parts, and process plans for the fabrication and assembly of the product) is the output of this phase.

Testing and Refinement: Multiple pre-production versions of the product are tested and evaluated during testing and refinement. Varying levels of the finished designs may be tested in this phase, and later-stage prototypes may include customers in the testing process, with products perhaps even being tested in the customers' own environment. The goal of this phase is typically to answer questions concerning performance and reliability and to identify any engineering changes that will need to be made to the final product.

Production Ramp-up: In the production ramp-up phase, the product is made using the intended production system, with the purpose being to train the workforce and work out any remaining problems. The units produced during this phase may often go to preferred customers and are carefully evaluated to identify any remaining flaws. Gradually, the production is ramped up into the ongoing production phase, in which the product is launched and made readily available. A post-launch project review may occur, in which the project will be assessed from both a commercial and technical perspective with the intention of identifying ways of improving PD processes for future projects.

The same authors also propose a more iterative process, which is presented in Figure 2.2 below.

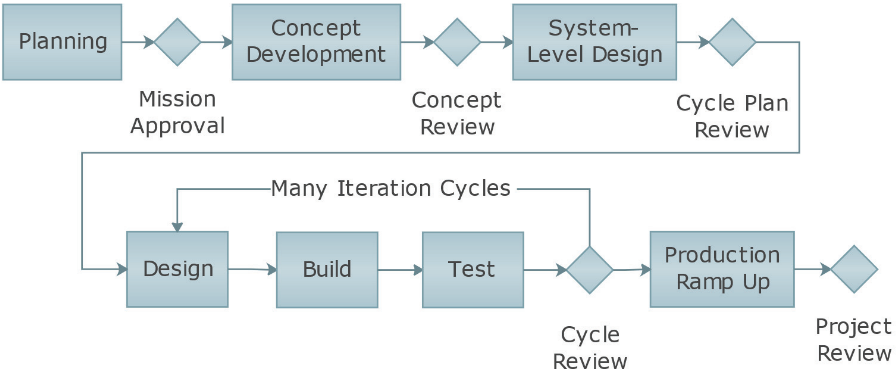

Figure 2.2 Spiral PD process (from (Ulrich & Eppinger, 2015)).

A particular type of PD process referred to as the spiral PD process was initially designed for the software industry and was adapted soon thereafter for many electronics products, but it has later been developed for application in manufacturing and other industries as well (McConnell, 1996). The model focuses on rapid processes such that the design-build-test cycle can be repeated many times. Teams may take advantage of this to create a more flexible and responsive PD process. The system-level design phase entails decomposition of a product into high-, medium-, and low-priority features, followed by several cycles of design, build, integrate, and test activities, starting with the most important features. The results of each cycle are incorporated into the next cycle, and priorities for the next cycle are consequently modified. Customers may be involved in testing in one or several cycles.

The development of the robotic cleaning system in this thesis to a large extent followed a mix of the generic PD process and a time-expanded spiral PD process. However, the steps following the production approval/cycle review steps in the models are not performed in this work. The understanding of design cycles, of which the spiral model is an example, has evolved over the years (Loch, Terwiesch, & Thomke, 2001). In 1969, the *generate-test* cycle was introduced (Simon, 1969) to illustrate the importance of generating new design alternatives in the PD process. Clark and Fujimoto (1989) expanded on this cycle with the addition of their *design-build-test* cycle, which emphasizes the importance of building prototypes. Thomke (1998) took this even further with the development of a *design-build-run-analyze* cycle to emphasize that the analysis of a test or an experiment is also important in product design. In this context, prototypes can be developed and constructed based on the outcome of such experiments, thus becoming the final outcome of a design cycle, and such is the case for the robotic cleaning system.

2.2 Prototyping

A prototype is defined as “an approximation of the product along one or more dimensions” (Ulrich & Eppinger, 2015) or an artifact that approximates one or more features of a product, service, or system (Otto & Wood, 2001). The dimensions could be appearance, components, functionality, or any other attribute related to a product. In the broad sense, the purpose of prototyping can be divided into four categories: learning, communication, integration, and milestones (Ulrich & Eppinger, 2015). Some of the same categories are repeated by Camburn et al. (2017), who state that the objectives of prototyping are, in descending order according to the number of citations, refinement, communication, exploration, and active learning. Industries often approach prototyping differently; typically, industries that focus on the development of large and complex systems are driven by fulfilling specifications, whilst more creative and agile firms focus on prototyping to explore and develop new concepts (Schrage, 1993).

Prototypes are often divided into different taxonomies, such as between those that address form and those that address function (Michaelraj, 2009; Otto & Wood, 2001; Pei, Campbell, & Evans, 2011). It is also not uncommon to make a distinction between the variable level of fidelity of a prototype with respect to the final model (Lim, Stolterman, & Tenenberg, 2008; Stowe, 2008) or between virtual models (simulations, visualizations, or computational approximations of behavior) and physical models (Stowe, 2008). Another distinction between types of prototypes is *milestone* prototypes, which are used to verify different aspects of the product and production processes. These are often referred to as *proof-of-concept, proof-of-product, proof-of-process,* or *proof-of-production* prototypes, depending on which aspect is in focus (Ullman, 2010). Prototype designs are rarely optimized; instead, the design process aims to produce a satisfactory design (Simon, 1969) based on what the manufacturers wish to prove with regard to the intended product. The testing of such prototypes is often singular events intended to demonstrate, verify, or explore the proposed solutions by obtaining either positive (compliant) or negative (non-compliant) results (Tronvoll, Elverum, & Welo, 2016).

As stated by Stowe (2008), a prototype is in essence a design representation of some aspect of a design, which could be its fit, form, or function (McKoy, Vargas-Hernández, Summers, & Shah, 2001; Vandevelde, Dierdonck, & Clarysse, 2004). A representation in this context is a visual artifact that allows individuals or entities to independently interpret the contents (i.e. some aspect of the performance or purpose) of the prototype (Walker & Thomas, 1985) of the prototype. One way of creating such an artifact is solid modeling, which allows a designer to construct and configure accurate virtual representations and to make necessary changes to them on the fly without the need for physical construction or tolerance stacking based on engineering drawings (Stowe, 2008).

Prototype development often represents a significant sunk cost, which can be recouped by establishing a successful product line. Therefore, in order to increase the chances of earning more money on the final product, it is important that prototyping efforts are efficient and have a high rate of success. While much work has been done on increasing the likelihood of success on the “business” side of PD, relatively few authors have focused on creating strategies intended to ensure success on the "engineering" side (Christie & Jensen, 2012). In relation to this missing focus on the "engineering" side of PD, virtual prototyping is used extensively in this thesis as a tool for increasing the likelihood of successful PD. Virtual models and computational analysis capabilities have now advanced to such a level that it is possible to satisfy certain design needs that once required physical (Stowe, 2008).

Innovation within aquaculture is dominantly approached from a linear and technology-oriented perspective (Joffre, Klerkx, Dickson, & Verdegem, 2017). Joffre et al. (2017) suggests that considering more than one perspective on innovation could be helpful in solving complex problems. Thus, this research considers prototyping from perspectives other than simply technological development.

When discussing non-physical prototypes in this research, virtual prototypes are the focus; this is due to their prevalence in many design processes when compared to other forms of prototyping, such as sketches or draft drawings. Two physical prototypes are presented in this thesis. Prototypes are often used not only for visualization but also for experimentation, and this is particularly important in early phases of PD (Criscuolo, Salter, & ter Wal, 2018; Rich & Janos, 1996; Veryzer Jr., 1998). The two prototypes presented in detail in this thesis were constructed for use in tests and experiments. Tronvoll, Elverum, and Welo (2016) proposed a framework for test environments in a prototyping context; see Figure 2.3 below. In this figure, X and Z are controllable variables and uncontrollable variables, respectively, which are used as inputs during tests. These inputs are related to the different classes of properties found in prototype testing; the prototype itself (P), the physical environment (E), the product structure (S), and human interaction (H). An output (Y) is also linked for each of these properties.

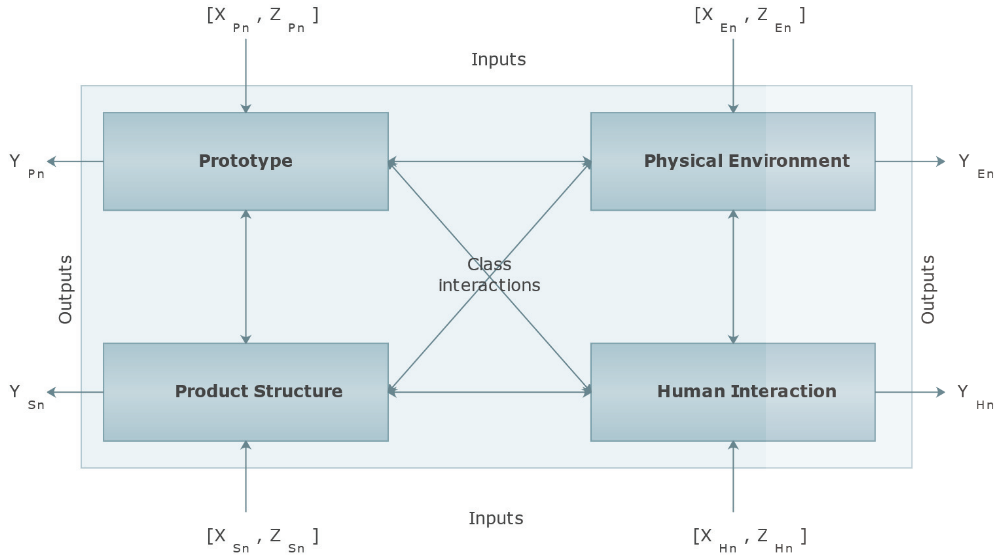

Figure 2.3 Model for characterizing prototype tests (from (Tronvoll et al., 2016))).

Highly comprehensive and analytical prototypes are generally not feasible to develop (Ulrich & Eppinger, 2015), and the use of virtual prototypes (analytical replication) prohibits the physical replication of any of the properties of a test environment (Elverum, Welo, & Tronvoll, 2016). Thus, in the context of testing a robotic cleaning system for FPPs, developing close-to-real test environments is the only method that allows for the truly accurate testing of all of the various multi-disciplinary aspects of the system. The only other method that would provide as many and as detailed answers is live testing in an actual FPP, but this would not be ideal due to the risk of bacterial contamination and the complications that this would pose for the day-to-day operations in such a facility.

2.3 3D Scanning

Taking manual physical measurements (which are time-consuming and generally result in low accuracy) followed by extensive computer-aided design (CAD) work is the traditional method for constructing virtual representations of production systems. Non-contact 3D imaging technologies such as terrestrial 3D laser scanning can be used to capture the spatial data of real production systems and to quickly develop accurate and realistic virtual representations. An example of such an application would be capturing measurement data concerning rooms and spaces and making their physical properties available in a digital format (Lindskog, 2014). Lindskog (2014) also states that 3D laser scanning is generally suitable for gathering comprehensive spatial data concerning production environments. Generally speaking, in 3D laser scanning, several scans are conducted to gather complete spatial information concerning large or complex areas. These scans are commonly aligned and combined into a single dataset using software. Such datasets (or "point clouds") comprise several million points, and filtering is usually recommended and required to reduce the data size (Randall, 2013; Shellshear, Berlin, & Carlson, 2015).

Three-dimensional scanning originated in the field of surveying, although it has gained increased traction in several engineering applications and scenarios, including heritage documentation, medical applications, crime scene documentation, industrial quality control, robot navigation, and machine vision (Date & Rebello de Andrade, 2015; Føre et al., 2017; Sansoni, Trebeschi, & Docchio, 2009). The raw data file containing the point cloud information is generally stored in a manufacturer's proprietary format. Unless the downstream processing software supports the format used, conversion into a standardized point cloud exchange format is required, for which several data formats are available.

Using 3D scanning devices rather than manual documentation methods can improve job site safety (Crilley, Dvorak, Harting, & Kutz, 2017). In some instances, the efficiency of data collection processes can be increased by approximately four-fold (Bures & Polcar, 2016), and the use of 3D scanning has also been observed to offer significantly improved information density and accuracy over traditional 2D documentation such as floor plans. The use of 3D point clouds for visualization and decision-support purposes has demonstrated that the communication between different engineering and project management departments can be improved. Costs and project durations can be reduced by improved visualization, and potential design errors can be eliminated in the early phases of the execution of a project. The information provided by 3D scanning also enables better decision-making. Three-dimensional scanning has also been established to be beneficial in improving offline robot programming (i.e. in simulations) (Berglund et al., 2016). Berglund et al. also state that, for offline robot programming, it is important to have fewer critical geometry errors than for manual work areas, which is why 3D scanning was considered important in capturing the geometry of the FPPs, as manual spatial capturing often produces errors or results in missing information.

2.4 Simulation – Offline Programming of Robots

Virtual prototyping has been used for several years, and such approaches can range from simple CAD models to complex simulations of systems. In addition, they may permit complex analysis and evaluation, as well as facilitate the production of parts or systems at earlier stages. The offline programming of robots is generally referred to as simulation. In the context of this thesis, simulation and offline programming of the cleaning robot refer to the same thing, and offline programming is used as a virtual prototyping tool.

Simulation has been utilized to identify and repair design errors (Baizid, Meddahi, Yousnadj, Ćuković, & Chellali, 2016) and to test equipment virtually to reduce commissioning/implementation times (Berglund, Lindskog, Johansson, & Vallhagen, 2014; Dahl, Bengtsson, Fabian, & Falkman, 2017; Hoffmann et al., 2010). It is possible to detect and manage problems offline, which reduces downtimes of and disturbances to a physical production system. In addition, early product designs may be used to test a production system's functions and capabilities (Kühn, 2006). Virtual testing of production flows, material handling, and robot welding are common examples of discrete event simulation (DES) applications. The models are based on logic, and they control sets of states that evolve interdependently through triggered events at discrete points in time within the model and virtual environments as the model is being executed. Such events may trigger other events to trigger as well, and, since DES models are based solely on the triggering of such events, nothing will happen unless an event is triggered. Consequently, should nothing happen, time will skip until the next event. This makes well-built DES models excellent at simulating long timespans of a modeled system, which can be very useful in terms of providing decision support (Nåfors, Bärring, Estienne, Johansson, & Wahlström, 2018). These events emulate events that could occur in a physical production system (Banks, Carson II, Nelson, & Nicol, 2010), and they are used to evaluate and predict a real-world system's behavior.

Many different types of systems can be simulated, such as, for example, airports or car manufacturing facilities (Banks et al., 2010). Discrete event simulation models have been common in the form of 2D visualizations, but, as CAD capabilities have grown, 3D DES visualizations have become increasingly common and important for the validation and verification of processes, aiding the communication of results, and attaining a shared understanding of both models and results (Banks et al., 2010; Jain, 1999; Rohrer, 2000). Discrete event simulation models require a great deal of data to give outputs that are correct and benefits the study in question (Nåfors et al., 2018), and previous studies have shown that such data could be provided by, for example, 3D scanning and that such scans can be beneficial in supporting DES modeling (Berglund & Vallhagen, 2013; Lindskog, Berglund, Vallhagen, Berlin, & Johansson, 2012).

Numerous methodologies for carrying out DES studies have been developed (Banks et al., 2010; Law & Kelton, 2013); however, all of them include a combination of the steps proposed by Musselman (1994), or derivatives thereof, which are as follows:

1. Problem formulation;

2. Model conceptualization;

3. Data collection;

4. Model building;

5. Verification and validation;

6. Analysis;

7. Documentation; and

8. Implementation

A few of these steps may be omitted, a few could overlap, and a few could be iterated. Overlap can occur when data collection continues during model construction owing to time constraints; alternatively, iterations may occur if the analysis fails to satisfy the requirements of the problem formulation process (Banks et al., 2010). Simulation is used as a synonym for DES throughout the remainder of this thesis.

White and Ingalls state (2015) that, in principle, simulation is much like running field tests, except that a physical or computational model replaces the system of interest. Simulation involves creating a model that imitates the behaviors of interest. There are three categories:

- Man-in-the-loop: Examples of this type of simulation include training or entertainment simulators, games that simulate driving, and flight simulators. Such an approach places emphasis on experimental learning by doing (or having fun).
- Analysis and design of artifacts and processes: An example of such a model would be a such as a finite-element model simulation.
- Analytical approach: In contrast to simulation, in an analytical approach, a model is expressed as a set of equations that describe system change over time; these equations are solved using standard mathematical methods. The result is a general closed-form solution.

The typical steps involved in a discrete event simulation are displayed in Figure 2.4 below.

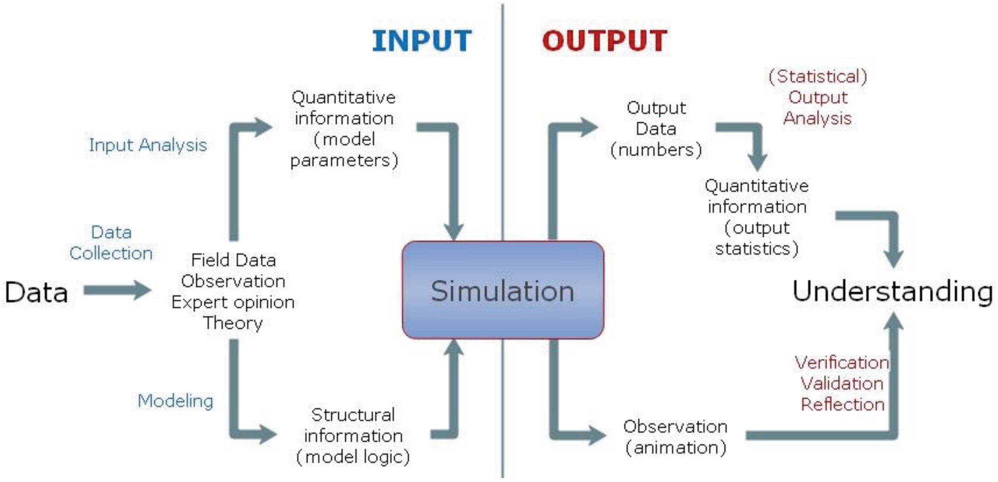

Figure 2.4 The activities in a DES study adapted from (White & Ingalls, 2015).

Simulation, in this case the offline programming of robots, is used to test the reachability and functionality of the proposed robot cleaning systems, and the programs generated can be directly loaded onto the second physical prototype as well.

2.5 Hygienic design – Design for Cleaning

EHEDG *Document #8 Hygienic Design Principles* describes "The criteria for the hygienic design of equipment intended for the processing of foods" (European Hygienic Engineering & Design Group (EHEDG), 2018). The criteria are formulated with the intent of aiding in the prevention of the microbial contamination of food products through improving the designs of equipment used for the processing of foods.

The guidelines presented in EHEDG chapters 4.1 "general", 4.2 "non-toxicity", 4.3 "stainless steel", and 4.4 "polymeric materials" all concern material choices: the materials used should be non-toxic, mechanically stable, and corrosion-resistant. In addition, they should have a suitable surface finish.

The guidelines presented in EHEDG chapters 5.1 "cleanability and decontamination", 5.2 "prevention of ingress of micro-organisms", and 5.3 "prevention of growth of micro-organisms" concern the functional requirements with regard to cleaning and contamination that equipment should adhere to.

EHEDG chapter 5.1 "cleanability and decontamination" states that equipment should be easy to clean. Chapters 5.2 "prevention of ingress of micro-organisms" and 5.3 "prevention of growth of micro-organisms" of the same document discuss the ingress of microorganisms and preventing their growth.

EHEDG chapter 6.2 "surfaces and geometry" states that product contact surfaces must be free of imperfections, direct metal joints should be welded, misalignments must be avoided, corners should be rounded, and threads should not come in contact with food. The surfaces should tolerate both the product and the necessary detergents and disinfectant and be non-absorbent.

The guidelines in EHEDG *Document #8 Hygienic Design Principles* correspond well with the findings of previous research in the field of hygienic design. In their book *Principles and Practices for the Safe Processing of Foods*, Shapton and Shapton (1993) state that the key criteria in hygienic design are as follows:

- Give maximum protection to the product;
- Ensure that the product contact surfaces that are necessary for processing will not contaminate the product and are readily cleanable;
- Provide junctures that minimize "dead" areas where chemical or microbial contamination may occur; and
- Provide access for cleaning, maintenance, and inspection.

Food contact areas are all surfaces that are directly exposed to the product and all indirect surfaces from which splashed product, condensate, liquid, or dust may drain, drop, or be drawn into the product.

According to (Lelieveld, Mostert, & Curiel, 2014), hygienic design must consider the following areas:

1. Safety: This refers to preventing contamination of the product with substances that would affect the health of the consumer, such as microbial (e.g. pathogens), chemical (e.g. lubricating fluids or cleaning chemicals), or physical objects (e.g. glass).
2. Cleaning: Equipment that is difficult to clean will take more time to clean and require more aggressive chemicals to eliminate microorganisms and product residue, with the result being both higher cost and reduced lifetime and availability for production.

3. Inspection: An equipment designer must ensure that relevant areas are accessible for inspection and/or validation (EHEDG Secretariat, 1997). Considerable testing of a design with regard to hygiene is often required to ensure sufficient performance (Holah & Thorpe, 2009).
4. Compatibility with processing function: Any processing equipment must perform its function, and a design with excellent hygienic design that is incapable of performing its function is of no use (Lelieveld, 2000). A compromise is often necessary between form and function, and more intensive and frequent cleaning may be necessary.

A considerable part of hygienic design is related to working with risk assessment in equipment design. Good hygienic design may also eliminate product "hold-up" within processing equipment, which refers to when a product could deteriorate and affect product quality when rejoining the main product flow; for example, good hygienic design may prevent batch cross-contamination (Moerman & Kastelein, 2014). Hygienically designed equipment may be more expensive than poorly designed equipment, but downtime may be reduced with good design due to less cleaning being required, which consequently results in more uptime for processing. Hygienic design has also become part of legislation regarding food processing in many countries, which establishes requirements for minimizing the risk of contamination and easily cleanable equipment.

One of the main challenges for a robotic cleaning system is the need for such a system to be flexible enough to be retrofitted into most existing FPPs. This is due to the fact that not many FPPs are built new each year, and the business side of the project would not be financially sound if only new FPPs are considered as potential customers. There are many reasons to renovate existing food processing plants instead of building new factories, and there is also a trend towards renovation as opposed to building a new factory. Some of these reasons are presented below (Moerman & Wouters, 2016a):

- It may be more costly to a build new facility than to renovate an existing location(s);
- Lack of permission to build a new factory on suitable grounds;
- The established logistical infrastructure; and
- The familiarity of vendors, material suppliers, and shipping/transportation services with the existing location of a facility.

It is has, however, been discovered that retrofitting into existing food processing plants is accompanied by increased risk of bacterial contamination (EHEDG Secretariat, 2004, 2014; Moerman & Wouters, 2016a) and that the threat increases with the installation time required. The same applies for service/maintenance tasks and the amount of time they take. It is therefore imperative to take this into consideration when developing complex systems and to make efforts to keep installation and commissioning times minimal to avoid unnecessary contamination risks.

2.6 Robots in the Food Industry

In addition to palletizing, robots have also been used in the food industry for the packaging of food. This changed in 1998, when ABB released the *Flex Picker*, which satisfied many hygiene conditions (Khan, Khalid, & Iqbal, 2018). The availability of this robot enabled robotization of tasks during the first stages of food production lines.

The first stage in a production chain in the food industry includes the actual production phase, where production equipment comes into direct contact with the raw components (e.g. raw fish). The manual worker is the main source of contamination in this step; as such, a high level of automation would avoid contamination points and is thus an important research aim. For robots to be used in this step, it is important that no contamination occurs to the products due to extraneous substances from the robot, such as lubricants or coatings. Furthermore, frequent cleaning is necessary to prevent cross-contamination. These two conditions lead to a myriad of requirements with regard to technical devices that can be used in food industry. The production step that involves raw food components is also faced with the difficulties associated with a high variety of products, as well as the non-rigidity and shape variation typical of natural products, which results in some problems and peculiarities that do not occur in other industries. There are also strict regulations and standards for the processing of foods that must be followed to ensure safe production of food. Automation of the processing of food requires development efforts on the part of the manufacturers, integrators, and users of food processing machinery. Standard industrial robots have thus far mainly been applied for the handling of packaged food (Mueller, Kuhlenkoetter, & Nassmacher, 2014). These challenges are summarized in Figure 2.5 below.

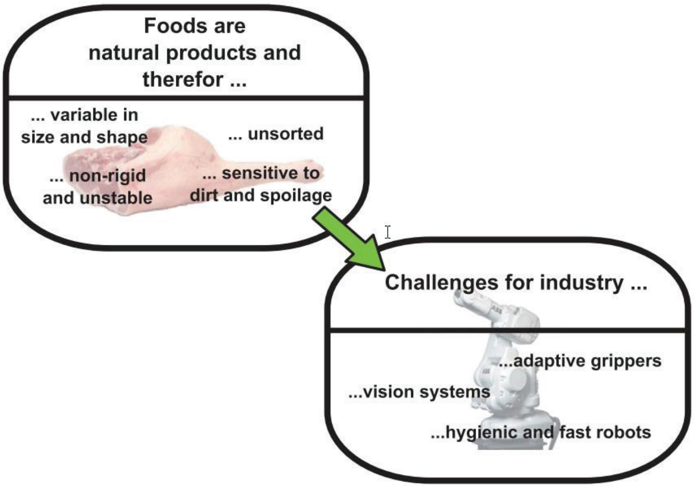

Figure 2.5 Typical challenges for robots in the food industry from (Mueller et al., 2014).

The challenges presented above have led to several requirements (Khan et al., 2018; Masey et al., 2010), which are presented below:

- Robot kinematics and dynamics: The serial and parallel robots already in use in the industry fulfill these requirements quite well. For an even better fit to the industry, a robot should have an optimized trajectory-planning algorithm and a low-inertia design, which reduces link mass.
- Control and dexterity: A robot’s control and dexterity must be at such a level that tasks that demand high precision, reliability, and repeatability can be accomplished. The effects of disturbances should be mitigated by the control system (Brogårdh, 2009).
- Hygiene: The main issue is that a robot should be able to work in a wet environment and ensure that food particles do not stick and cause bacterial growth. All external parts must be visible for inspection and accessible for annual cleaning. The robot should preferably be made of stainless steel. Joints must be easy to seal.
- Productivity: There is an ever-increasing trend in terms of a demand for greater productivity, which robots for the industry should help to satisfy.

- Worker safety: If a robot is to work alongside humans, it should have a low-inertia design and be capable of monitoring its position. There should also be a virtual safety barrier.
- Cost: Flexible or modular robot designs ensure rapid and easy integration into existing product lines. A simplified design may be necessary, and it may not be necessary that the robot has six degrees of freedom.
- Ease of operation and maintenance: For easy operation, a robot must be of an appropriate size in terms of its footprint and the available workspace whilst ensuring sufficient reachability to accomplish the required tasks. Generally speaking, a very large footprint is not suitable. The appropriate industrial protection class should be selected.

3 The Current Cleaning State of the Art

The following investigation into current state-of-the-art practices in terms of cleaning is based both on literature research and the experience and knowledge gained throughout the course of the project. Thus, the following material is presented as its own chapter instead of being included in Chapter 2.

Most bacteria are either neutral or beneficial for humans. Bacteria contribute to many processes that are essential for life on earth and human health; for example, probiotic bacteria are essential in the digestion of food in the gut and contribute to a strong immune system in both human and animals. Other bacteria are used in medicine to create antibiotics, and others still are used in food production to make fermented foods. However, about one in 1,000 bacteria is pathogenic, and even this tiny demographic represents the third-most lethal killer of humans worldwide. Some of the most virulent illnesses, ranging from plagues to tuberculosis, are caused by bacteria (Bryson, 2004).

To address the risk of bacterial contamination, processing plants must be thoroughly and frequently cleaned (Christi, 2014; Windsor & Tatterson, 2001); in particular, fish processing plants need to be cleaned daily. The current state-of-the-art cleaning practices are manual operations, which are usually conducted at night due to the fact that most FPPs have two operating shifts during the day. In the overall scope in a production system of fish, the efficiency and reliability of said system are key enablers in terms of being profitable (Ohno, 1988), which requires stable processes. Manual operations are subject to human error; humans are, particularly at night, prone to underperform or may be distracted by other thoughts. There are also significant expenses related to chemicals and water. Moreover, the chemicals used produce spray clouds inside processing plants during cleaning, which, as can be seen in Figure 3.1 and Figure 3.2, pose health hazards to cleaning personnel. Furthermore, manual cleaning causes significant strain to the body as a result of the repetitive movements required. The hoses that are used for spraying water and chemicals are heavy, and owing the high-pressure systems used, they are difficult to handle. Furthermore, cleaners may also be required to climb on equipment to reach inaccessible areas. Overall, the manual cleaning of FPPs requires a considerable amount of heavy lifting.

The remainder of this chapter focuses on describing the current state of the art with regard to how current cleaning operations and the control measures of the operations are performed. Lastly, a brief overview of the use of robotics for cleaning is presented.

Figure 3.1 Environment of an FPP and the use of a manual cleaner during cleaning.

Figure 3.2 Environment during cleaning in an FPP.

Currently, there are no alternatives for hygienic production of fish other than cleaning of the FPP. A general cleaning process for FPPs is formulated in (Mariott & Gravani, 2006) and presented below.

1. Cover electrical equipment.
2. Remove large debris.
3. Remove soil deposits from the equipment, walls, and floors, proceeding from top to bottom towards the drains.
4. Disassemble equipment as required.
5. Pre-rinse the equipment with water at 40 °C or less.
6. Apply a cleaning compound effective against organic soil (typically an alkaline cleaner), at a temperature lower than 55 °C.
7. Wait for approximately 15 min to allow the cleaning compound to work.
8. Rinse the equipment with water at 55–60 °C.
9. Inspect equipment and the facility for effective cleaning.
10. Apply a sanitizer, typically a chlorine compound.

This procedure is similar to those typically used in Norwegian FPPs and described in previous research (Løvdal et al., 2017). In addition, it is also similar to industry guidelines for cleaning, both those of FPPs and external companies that provide cleaning services. Lilleborg, for instance, recommends a similar procedure, which corresponds to the current industrial practice (Lilleborg, personal communication):

1. Rough hosing down of the equipment with water, clearing debris, bits and pieces. Water temperature below 40 °C, usually sprayed through nozzles which gives 30-40 liters per minute and a 15-20 ° spread with a pressure of 25 bars.
2. Apply foam to the whole facility, usually chlorine alcaic foam, which should stay on the equipment for approximately 15-20 minutes. This foam nozzle sprays 200 liters of foam per minute.
3. Rinse the facility with water, also at 15-20 ° spread with a pressure of 25 bars
4. Apply sanitizer, which should be left to work for 15 minutes.
5. Rinse off with hot water, 60 °C, with a 25 ° spread nozzle which sprays 30-40 liters per minute at 25 bars. This allows the equipment to dry fast.

The food safety of Norwegian salmon products is largely determined by the presence of *L. monocytogenes* (Løvdal, 2015). The problem of bacteria in FPPs is involved, where *L. monocytogenes,* in particular, is subject to thorough investigation. Although *L. monocytogenes* is likely to be consistently reintroduced into processing plants from a variety of sources, including raw fish material, water, and personnel, there are indications that the *L. monocytogenes* found at environmental sites and the *L. monocytogenes* found in raw material represent different bacterial populations (Hoffman, Gall, Norton, & Wiedman, 2003). This has led to the hypothesis that persistent *L. monocytogenes* strains represent the predominant source of contamination in processing plants (Hoffman et al., 2003; Rørvik, Aase, Alvestad, & Caugant, 2003). Earlier studies have demonstrated that salmon processing plants often harbor their own specific populations of *L. monocytogenes* subclones (Rørvik et al., 2003; Wulff, Gram, Ahrens, & Vogel, 2006). These persistent strains may be specially adapted to the processing plant environment and be extremely difficult to sanitize using standard hygiene procedures (Porsby, Vogel, Mohr, & Gram, 2008; Vogel, Huss, Ojeniyi, Ahrens, & Gram, 2001). One suspects the fish to be susceptible to contamination during processing (E. (Nofima) Heir & Langsrud, 2014), as a result of poorly hygienic design or through rebuilds, repairs, maintenance, or personnel or visitors in the facility (E. Heir, Langsrud, & Hagtvedt, 2015). The varying cleaning performance by the operator combined with poorly hygienic design are additional aspects suspected of contributing to the persistence of house strains. The persistence of *L. monocytogenes* in food processing plants has been hypothesized to be an important factor in and the root cause of a number of listeriosis cases (Ferreira, Wiedman, Teixeira, & Stasiewicz, 2014; Nakari et al., 2014). However, this view is not well-founded in the research literature and may be outdated; as such, it has been challenged by the fish processing industry.

The alternative hypothesis is that the threat of the establishment of persistent *L. monocytogenes* colonies in the plants is no longer the main problem; rather, the issue may be that it is continuously introduced into slaughterhouses in varying amounts through the year, depending on weather and environmental factors. This hypothesis is founded on data collected by the industry itself through internal control measures showing that *L. monocytogenes* is regularly present in the ambient environments outside of slaughterhouses, at salmon sea-rearing sites, in well boats transporting salmon to FPPs, and so forth (MOWI, personal communication), and it thus may be the case that salmon processing in itself contributes to contamination of the proximate environment. Modern molecular tools for bacteria typing (whole genome sequencing) have recently been used for the epidemiological surveillance of *L. monocytogenes* (Moura et al., 2016) and are also showing great promise in tracking the spread of *L. monocytogenes* in the fish industry (Fagerlund, Langsrud, Schirmer, Møretrø, & Heir, 2016). The transmission routes of *L. monocytogenes* in the fish processing industry are not well-documented, although some problematic areas and sources of contamination have been identified (E. Heir & Langsrud, 2013; Løvdal et al., 2017; Rotariu, Thomas, Goodburn, Hutchison, & Strachan, 2014). Thus, the origin of bacterial contamination, the vectors, and the environmental factors determining the spread and establishment of pathogens are not well-known.

It is quite common for FPPs to perform hygienic control using adenosine triphosphate (ATP)-monitoring instruments, as they are a rapid and cost-effective means of identifying failures in the sanitation process (Møretrø, Normann, Sæbø, & Langsrud, 2019). However, this approach does not indicate which bacteria are present, and the detection limit for bacteria is low. Many FPPs also devote a great deal of resources to monitoring the cleanliness of their processing environments by sampling and analyzing for total bacteria using conventional cultivation-dependent methods (Møretrø & Langsrud, 2017), such as for the pathogenic bacteria *L. monocytogenes.* These are relatively expensive, and it may take several days to obtain the results, meaning that “live” control of bacteria is not possible (Hawronskyj & Holah, 1997).

Robotic cleaning systems have already been well-established in the literature. However, most robotic cleaning systems were focused on the cleaning of flat surfaces, such as floors (Palleja, Tresanchez, Teixido, & Palacin, 2010), walls (Lee et al., 2018), windows (Houxiang Zhang, Jianwei Zhang, & Guanghua Zong, 2004), and solar panels (Jaradat et al., 2015). Cleaning systems may be able to operate in large areas; however, they are limited to moving in two dimensions, and they typically do not operate in 3D space. However, there are exceptions. Cleaning systems such as hull cleaning systems (Ortiz et al., 2007) and car/truck washers (Yu, Kurnianggoro, & Jo, 2015) can operate in three dimensions and can clean objects of arbitrary shape. However, to the best of the knowledge of the author, there are no research works in the literature focused on robotic cleaning of FPPs. Conventional robotic manipulator designs do not fulfill the requirements of a robotic cleaning system for FPPs (Bjorlykhaug et al., 2017).

Efforts have been made regarding the automation of cleaning in other areas, such as the cleaning of tanks that are used in aquaculture (Mcrobbie & Shinn, 2011). Systems for cleaning in place, such as those used for cleaning pipes and other closed systems, are common and well-developed to clean pipes and other closed systems (Cramer, 2013).

In this chapter, focus has been on how cleaning is currently done in the industry. It can be concluded that the current cleaning practices have room for improvements, and that these will likely improve the overall delivery of safe fish products. The next chapter will focus on how experiments are carried out in this thesis in an effort to improve the current cleaning practices.

4 Developing the Proposed Robot Cleaning Systems

In the previous chapters, the background, problems, and theories required to understand the complexity of developing a robotic cleaning system were presented. This chapter presents the concepts and prototypes of the robot cleaning systems that were developed and tested during this project, as well as how they evolved and were developed throughout the course of the project.

To achieve a system capable of the robotic cleaning of FPPs, more than just a mechanical arm is needed: A system is also needed around the mechanical arm to provide it with a suspension structure and additional maneuverability. In addition, cleaning systems are needed to supply high-pressure water and chemicals, nozzles of different varieties are needed to spray water or chemicals in the appropriate way, and a means of transporting the arm is needed to provide the system with enough reach. Altogether, these components and requirements constitute the robotic cleaning system developed in this thesis, and this system will have many interfaces with the rest of a processing facility.

The main issue is thus the mechanical solutions that the system is based on. All further advancements regarding solutions for programming and new technologies such as vision systems or business models will be futile without a well-functioning mechanical solution. Thus, such a solution is the focus going forward. This is evident based on the discussion in Chapter 1.2, in which most of the identified problems were found to relate to the mechanical fit of a robotic cleaning system and its installation in different FPPs.

There is currently no well-established method for testing complex machines for fish processing. Machines are typically modeled in 3D CAD and built based on the resulting drawings, with mistakes being corrected when they occur (which they often do). The actual physical testing of products often proceeds at FPPs or with dead fish at an OEM’s site. A major issue with testing at an OEM’s site, however, is that the fish used for testing, which typically have been dead for some hours and may even have been frozen, do not behave in the same manner as live or freshly killed fish. Of course, dead fish do not behave in the same manner as living fish, but it is important to recognize that fish that have been dead for several hours differ in terms of stiffness, slipperiness, and dexterity when compared to freshly killed fish. This often results in revisions to the design and functionality of machines being required after they have been installed and tested at FPPs.

Performing extensive testing at FPPs is also often expensive and may not be possible from a practicality perspective. In addition to fish behavior, the environments found in FPPs are hard to replicate, particularly the humidity and the fish residue encountered during production and the spray fog of water and chemicals during cleaning. To go further into the context of cleaning, no models of bacteria behavior in FPPs exist, creating uncertainty as to why bacterial contamination occurs and how cleaning actually works with regard to preventing it. Knowledge concerning the role of prototyping in an industrial setting is scarce (Elverum & Welo, 2015), meaning that an exploratory and inductive research approach may be appropriate (Maxwell, 2013). Accordingly, the only way to determine whether and how well a robotic cleaning solution works is to perform physical testing with prototypes in an industrial setting.

Subsequently, with regard to the development of a custom cleaning robotic solution, a controlled environment that resembles an actual FPP is needed to answer questions related to such a system's environmental tolerance, cleaning results, and bacterial behavior. A real-life environment is required because the development of advanced, comprehensive analytical simulations of complex systems, sub-systems, and surrounding environments is generally not feasible (Ulrich & Eppinger, 2015).

4.1 Product Development Process and Prototyping Activities

The PD process in this work took the form of an interdisciplinary and collaborative undertaking where researchers from different scientific fields worked together to develop a common understanding. The initial needs and requirements were identified and described in collaboration with the OEM, the buyers, and, to some extent, potential users of the equipment. Input was also gathered from the workers who would potentially manufacture and install the equipment. The PD processes presented in Chapter 2 were utilized to develop prototypes of the robotic cleaning solution. There exists very little literature regarding PD in the fish processing industry or on developing products for fish processing. As such, the general process in Chapter 2 was considered a good place to start, even though the *testing* phase proved slightly difficult due to the aforementioned challenges. The following chapters, particularly Chapter 4.1.2, provide insights into how further near-industrial testing was approached in this research. The focus is on the role of the PD of equipment within the environmental conditions in which seafood production is conducted, and this work can thus be considered a noteworthy contribution to the existing scientific body of knowledge on FPE. Parts of the theory presented in Chapter 2, in addition to the challenges described in Chapter 1.2, is also part of the results of this work and is the outcome of the *planning* phase of the PD process. Known industry requirements from Optimar's previous work in with FPPs were considered during the planning phase, where the goal of the project is defined as being the same as the overall objective of this thesis presented in Chapter 1.3: "*Exploration of how fish processing plants may be cleaned more effectively through the use of robotics*".

Usually, companies that produce FPE define product requirements in close collaboration with their customers as part of the PD process. In general, there is a strong dependence on product acceptance by the buyers of FPE, which limits a design team in terms of exploring solutions that a customer perceives as less relevant (Bar, 2015). In order to explore different solutions, the choice was made not to involve customers to a significant degree after exploring the initial requirements in this research. However, the solutions that were tested were very industry-near due to the Optimar AS' inherent focus on delivering value to customers.

The PD activities were terminated prior to the *production ramp-up* phases from either of the two PD processes presented in Chapter 2.1. The current state of affairs after two full-scale physical prototypes is a *cycle review* containing a set of requirements and several ideas regarding moving the work forward and implementing the recommended changes. Starting a new iteration cycle is the next step.

4.1.1 Prototype 1 – UR10

The industry requirements and theory from the planning phase served as the basis for the initial concept developments (see Figure 4.2), during which one concept was chosen to be built as a full-scale physical prototype. Computer-aided design models (i.e. virtual prototypes) were used extensively to plan, develop, and, to some degree, test the first prototype, both on the component (detail design) and system levels. The test was planned together with Nofima and was formulated to determine how well the robotic cleaning concept is able to clean a critical product in an FPP, namely an electric stunner.

Further detail designs were developed from the concept using traditional CAD tools, and simulation software was used as an additional tool in the PD process, as presented in Figure 4.2. The simulation of the movements of the robot and linear rail presented in Figure 4.1 was evaluated, which led to the discovery of several design errors and provided insight into the reachability (and, consequently, the performance) of the system. The required design changes were implemented prior to the actual tests. The robot and rail were programmed online, meaning that the UR10's teach pendant (a control box for programming the motions of the robot) was used. This is not an optimal solution in FPPs, but additional efforts would have been required to bridge the gap between the simulation environment and the UR10 robot to facilitate offline programming. During pre-testing, the robot's movements were programmed and tested iteratively, and further design errors were identified and subsequently fixed.

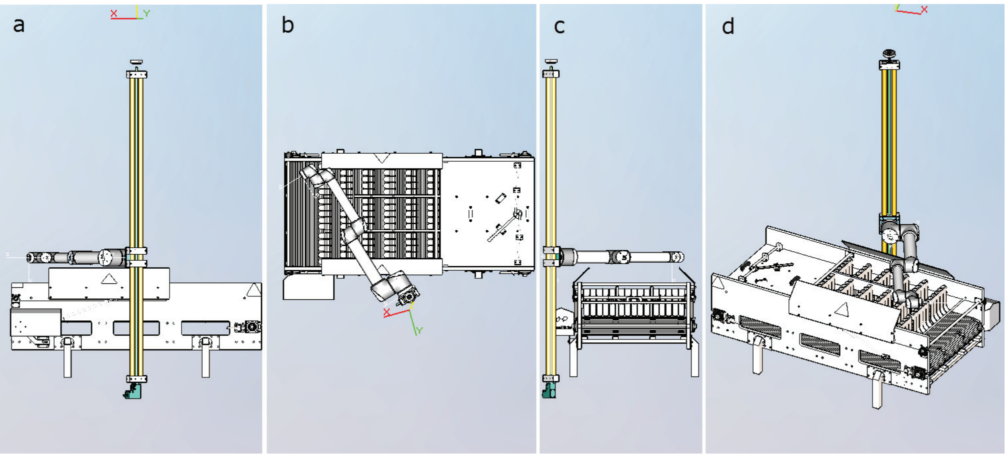

Figure 4.1 Simulation of robot and manipulator movements for Prototype 1. Note that the frame used to suspend the linear rail is not present on the virtual model used for simulation. This figure presents the side (a), top (b), front (c), and isometric (c) views.

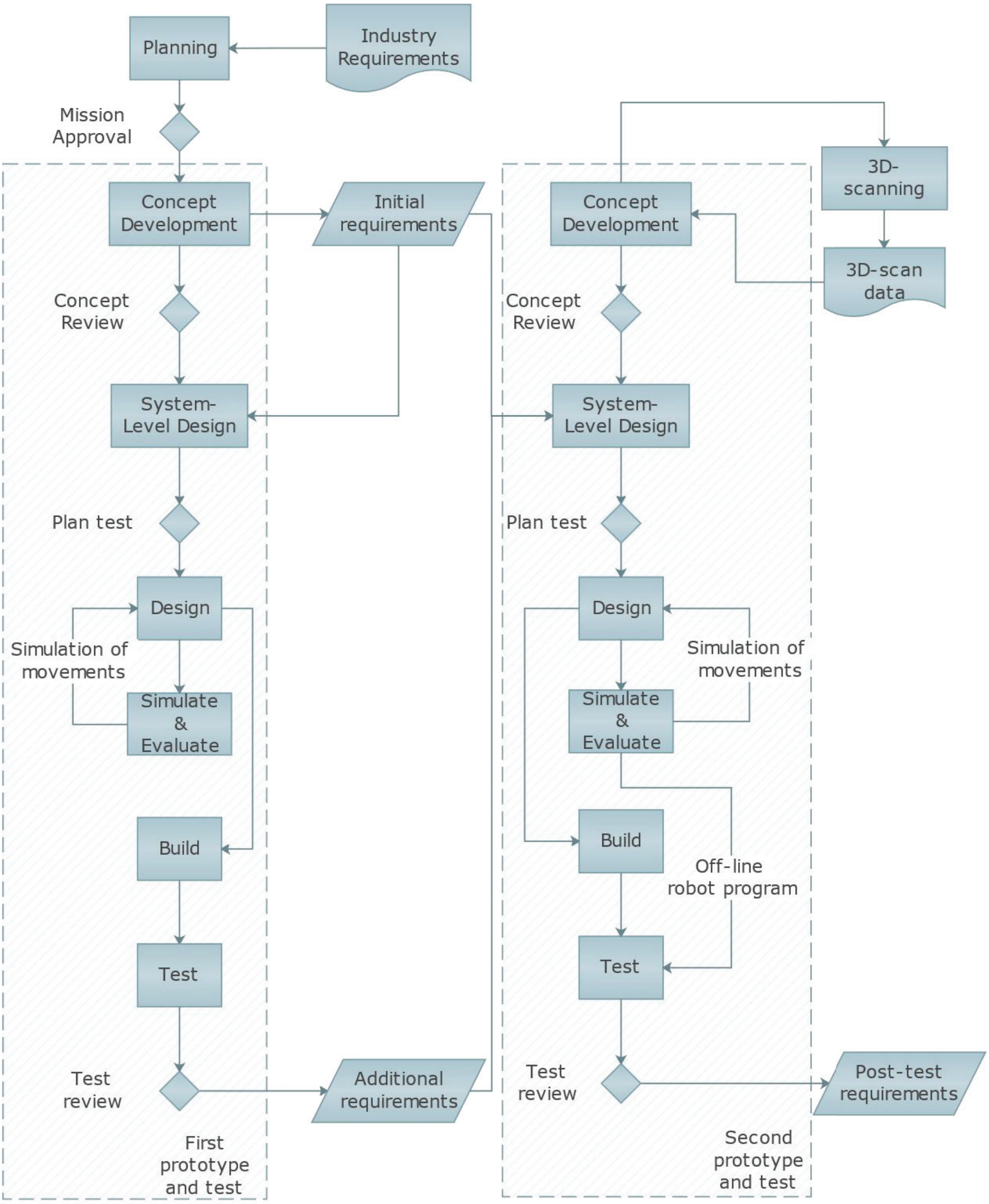

Figure 4.2 Product development process during the project.

4.1.2 Prototype 2 – Custom Manipulator, Trolley, and Rail

The outcome of the testing of Prototype 1, which was a cleaning test, provided answers to many questions regarding how a robotic cleaning system should function; these answers led to a new set of requirements, which were added to the existing requirements. A major finding was that an entirely new approach was needed, which led to a completely new cleaning system concept involving a custom-built manipulator, a rail, and a trolley to perform the cleaning. Thus, instead of reiterating the design-build-test as suggested in the spiral PD process presented in Figure 2.2, the design process was restarted based on the concepts that had been developed in the previous test. Computer-aided design tools (virtual prototypes) were used extensively in much the same manner as for Prototype 1. As can be seen in Figure 4.2, the requirements that were identified during the first test were fed into the development loop of Prototype 2.

Simulation was also used here as a design and prototyping tool; in addition, the resulting simulation sequence was used directly to program the robot. Furthermore, 3D scanning was applied as a design tool for obtaining geometrical data and performing collision tests. The cleaning test for Prototype 2 was also planned together with Nofima, who are experts on microbiology in fish processing, and was somewhat extended compared to the first test. A more comprehensive test was needed to obtain more answers; thus, two critical products were chosen for cleaning: an electro stunner, as in the first test, and a gill-cutting conveyor. Both are important to clean since they are situated early in the processing line, and contamination here may thus spread to the whole facility.

The issue of replicating the environment of an FPP has previously been mentioned in this chapter. It was realized during this round of testing that a laboratory environment resembling that found in an FPP would be required to draw conclusions regarding the industrial applicability of the solution.

4.1.2.1 Prototype Lab

An abandoned FPP is situated within walking distance of Optimar AS' location and is currently only used for storage. It had not been used by Optimar for testing previously, but, during an inspection, it was discovered that it contained an existing room which was fitting for cleaning tests. Its ceiling, walls, and floor are all industrial-grade, it has access to water and electricity, and drainage in the floor. An agreement was reached with the current users of this abandoned facility to let Optimar and the project group use this room for testing.

The room is 5 x 7 x 3 m (width x length x height) and photos depicting it are presented in Figure 4.3 below. Note the ventilation unit in the back of the room, which would be an obstacle for a robotic cleaning system. A layout of this room does not exist, as the building is old and has been remodeled several times.

Figure 4.3 Photographs of the prototype lab.

The test room was emptied, and a frame was built in place such that it was possible to suspend the robotic cleaning system from the ceiling. Pre-existing equipment used for testing by Optimar AS was placed inside the room. Computer-aided design drawings of this equipment are non-existent due to its age, but it is still valid for use in a test such as this, and the resulting room layout served as a reasonable approximation of a situation in which a robotic cleaning system would need to be retrofitted into a facility with an absence of documentation of both equipment and the facility infrastructure. The resulting test lab is shown in Figure 4.4.

Figure 4.4 Test lab prior to the installation of the robotic cleaning system.

4.1.2.2 Custom Robotic Cleaning System

A custom manipulator was designed such that it satisfies the requirements of hygienic design guidelines such as those presented in Chapter 2.5 and in Publication 3 (Lars Andre Langoeyli Giske et al., 2017). Industrial components are used for servo motors, gears, screws, nuts, valves, wheels, sensors, nozzles, hoses, belts, springs, and cable glands. The links between the joints of the manipulator are standard industrial pipes cut to the required specifications. The main components of the joints are made of laser-cut AISI 304 steel plates that were welded together, as is the case with the rail and trolley. Virtual prototyping was used extensively, and every custom-made part was designed using the industrial CAD system Inventor 2016 (Autodesk, 2019). Several concepts were developed and evaluated, and detailed designs of the manipulator, the trolley, and the rail of the chosen concept were combined into a single detailed CAD model. Thereafter, complete detail and system production drawings were made. Parts were manufactured at the Optimar AS location or manufactured by suppliers based on the specifications provided in the drawings.

The test lab was 3D scanned; the procedure is presented in Paper 4 (Lars Andre Langøyli Giske, Benjaminsen, Mork, et al., 2019). The scan data was transformed into solid models and used in Visual Components (VC) (Visual Components, 2019) as resources in the virtual simulation environment. The CAD drawings of the rail, trolley, and custom manipulator were imported into the simulation environment. As the manipulator was custom-made, a custom control system was also needed, and the kinematics of the custom manipulator were developed and implemented in VC. This made it possible to not only program the cleaning paths on the test equipment but also to check the reachability of the manipulator and for collisions. The required design changes were made in Inventor, and new models were exported into VC for further analysis.

The benefits of using VC went beyond the ability to perform collision testing and reachability tests; the simulation program was also used to directly move the physical prototype by creating a programmable logic controller (PLS) program that reads the simulation program and translates it into movements for each servo motor individually. This offline programming method is essential for achieving rapid installation times at FPPs.

The cleaning test for Prototype 2 was also planned together with Nofima, but it was somewhat expanded in comparison to the first cleaning test. As noted previously, more FPE (an electric stunner and a gill-cutting conveyor) was introduced to further test the sophistication and applicability of the solution. As mentioned before, it is crucial to clean such equipment well, as it these components situated at the start of fish processing lines. Any contamination here will likely spread throughout the facility. Such equipment is also often covered in fish residue and blood, as can be seen in Figure A.8 and Figure 1.2.

During the pre-testing of the custom solution, the manipulator's movements were simulated, exported to the PLC, and tested iteratively. Furthermore, additional design errors were identified and fixed. On occasion, only the manipulator paths were adjusted, but some design changes were also made.

4.2 Robotic Cleaning System Requirements

The first research question, RQ1, asks how a robotic cleaning solution can outperform manual cleaning operations. To achieve goal identified in this question, it was necessary to identify essential requirements and ensure that the robotic cleaning system could fulfill them. The background of the requirements that a robotic cleaning system should fulfill is complex. The foundation is that a robotic cleaning system should solve the problems and challenges presented in Chapter 1. In addition, some requirements were formulated based on the theory presented in Chapter 2, some on industry experience, some on discussions with FPP operators and owners, and some on the results of the test performed during the course of this project. Many were clear from the beginning, while others evolved over the course of the project, and some were identified through working with the prototypes. The requirements presented in the following lists answer mainly RQ1.

The initial requirements, which came about during the *planning* phase of the project, are presented below:

- Safety for personnel and equipment in the FPP:
  When working with robots, safety is important. The concept is that a robotic cleaning solution will replace workers, and there should thus not be personnel in the vicinity when the robot is cleaning. However, safety measures such as sensors on doors and other places to detect movement and a sign-off system to ensure that no humans are present should be installed in FPPs should such a system be implemented.

- Low cost:
  Initially, there will be uncertainty regarding how well the solution will work, especially over a longer timeframe. Even though considerable savings are foreseen as a result of the introduction of such a system, costs must be kept low.
- Able to be retrofitted into most existing FPPs:
  As very few new FPPs are built each year, it is necessary to develop and design a robotic cleaning system with retrofitting in mind. If it is not possible to retrofit such a system into existing plants, there will be no economic gain in developing it from an OEM's perspective, as the sales volume will be too low.
- Ensure satisfactory hygiene:
  The main objective of a robotic cleaning system is to improve the overall hygiene in FPPs, meaning that the solution must clean at least as well as current methods.
- High/long reach of the robotic cleaning system:
  In order to make a robotic cleaning solution economically viable, it must have a long reach to avoid the necessity of installing several robots.
- Should replace several cleaning operators:
  The economic gains promised by the project will require that several cleaners be replaced by the robotic cleaning system to be achieved.
- Should be able to clean a large portion of an FPP, such as the slaughtering area:
  This point also relates to the economic aspect of the project. For a solution to be able to replace several cleaners, it must cover a large portion of a facility.
- The robot's ability to tolerate the environment in which the robot is planned to operate:
  Unless the robotic system tolerates the environment in which it will operate, it will not be installed. Such a degree of tolerance can be achieved by using industry-standard materials and methods for protecting components.
- The robot's ability to tolerate the chemicals which are used during cleaning:
  As per the previous point, the robot system must be able to tolerate the chemicals used in cleaning procedures. It will not be economically viable to perform service and replace parts on the system continuously (although some service and replacement of parts will be necessary, but such maintenance will only be expected after a reasonable period of time has elapsed).
- Dexterity throughout the working area:
  Dexterity is related to reach, but a long reach alone is not adequate. A certain degree of flexibility and coverage is needed, as some machines must be cleaned from several angles and from both above and below.
- Short installation time to reduce impact on production time:
  The constant activity in FPPs throughout the year requires the installation time to be short to avoid having to halt production more than is necessary.

The following additional requirements were identified after the first cleaning test:

- Low weight:
  By keeping the weight of the robotic cleaning system low, the surrounding equipment (e.g. the trolley and the rail) may be scaled down. The complexity of installing the system will also be less with a low weight. This leads to the next point, namely the small footprint.
- Small footprint:
  A small footprint results in a less intrusive system.
- Avoidance of intrinsic contamination - hygienic design:
  The system should feature a hygienic design and not pose new contamination threats

in terms of either microbiological or chemical contamination, alien substances and particles. The robotic cleaning solution cannot introduce new contamination sources (e.g. oil, chemicals, or metal debris).

- Sufficient stiffness:
  Increasing stiffness in the suspension to allow scrubbing or other innovative cleaning methods requiring force on the part of the robot. Certain parts of the equipment in FPPs are more susceptible to growing biofilms. A robotic cleaning solution should take into account the potential adoption of novel end-effectors such as scrubbing brushes to enhance the cleaning of such parts further.
- Minimal obstruction to the workspace during normal fish production:
  Normal fish production should not be disturbed or obstructed by the robotic cleaning system or accompanying equipment, as this could affect production capacity.
- Custom nozzle/nozzle arrangement may be necessary:
  In order to reach all areas and hose them down adequately, a custom nozzle and/or nozzle arrangement may be necessary. It may even prove simpler to solve some issues associated with the robot’s dexterity and flexibility with nozzles instead of complex cleaning paths or specialized end-effectors.

Additional requirements were also formulated during the course of this project. These are not presented in Figure 4.2, since they were not developed at a specific time or during a specific process but rather evolved naturally during the project.

- Few changes to existing processing plant infrastructure:
  Fish processing plants in the NAI are often fine-tuned to a specific throughput and changing this is very resource-intensive and time-consuming and may result in an FPP with a lower capacity. If a robotic cleaning system requires considerable changes, it may not be economically viable to implement it.
- Short commissioning time to reduce the on-site time required after installation:
  This requirement is related to the short installation time. Traditionally, online programming is performed on robot manufacturing cells. This both takes a great deal of time and is resource-intensive. A robotic cleaning system should be up and running shortly after installation to avoid delaying production of fish; furthermore, with regard to contamination risks, limiting the period of time in which external workers operate in a facility is preferable.

The following additional requirements were identified as important after the second test, and should be considered in further advancements for robotic cleaning:

- A robotic cleaning system should be easy to use for FPPs (e.g. push a button to start cleaning):
  Ideally, a robotic cleaning solution should start and run at the push of a button. Workers in FPPs are accustomed to automatic operations such as cleaning-in-place running by themselves. This feature will ensure that the solution will be used after implementation.
- Reach is more important than stiffness:
  As the cleaning robot is not intended to perform any tasks that require any particular level of accuracy, the focus will be mainly on reach. Performing cleaning requires little stiffness and strength on the part of the robot.

Many of these requirements are covered explicitly in the publications presented in the section of Appended Papers on page 93. The requirement that few changes be made to existing FPPs is related to several of the other requirements. By ensuring that the robot is lightweight and has a small footprint, the entire mechanical solution around it can also be kept to a small size. This results in shorter installation time, as the robot will be less complex to implement, and will also enable installation in a greater number of existing FPPs than a complex solution that that may significantly disrupt an FPP's infrastructure. Bearing modularity and customization capabilities in mind will also aid in making a robotic cleaning solution viable for a greater number of FPPs.

The requirement of good cleaning results is not explicitly listed in Publication 2, but it is implicitly required that the robot clean effectively and well in order to make it a sellable solution. This is also related to the number of cleaners that the robotic solution is intended to replace.

The remaining requirements are addressed throughout the following chapters of this thesis. The concepts and prototypes are presented in the next sections. A complete overview of the extent to which the prototypes satisfy the requirements is presented in Table A.1, which can be found on page 83. A summarized version of this table is presented in Table 2 on page 49 as well.

5 Results

This chapter presents the main results of this work, which is a summary of the appended papers. Some details that are presented here are not covered in the papers. Amongst them, the details around the building of the test facility, which was an important part of the testing. The results are presented in the context of Figure 1.3 and divided into the categories of *cleaning of FPPs, robotic cleaning system, virtual factory layouts, and prototyping and hygienic design.*

The above considerations are all considered necessary elements to enable robotic cleaning of fish processing plants, in addition to other aspects that this thesis has not covered. Such aspects could include, but are not limited to, vision system development for detecting contaminated areas and feeding this back to the robot system to allow "on-the-go" adjustments of cleaning paths. Nevertheless, the experiments done in this project provide indications that robotic cleaning of fish processing plants could be possible in the future, with a cleaning quality that is equal or surpasses manual cleaning procedures.

5.1 Robotic Cleaning Systems

Leaning on the theory presented by Thomke (1998), the prototypes presented next were developed and constructed based on the outcome of experiments (both physical and virtual), and the iteration based results obtained should thus themselves be considered as the final outcomes of design cycles and results. Knowledge concerning the role of prototyping in an industrial setting is scarce (Elverum & Welo, 2015), and the work done in this thesis may aid in contributing to the knowledge in this field. Unfortunately, the available time and resources did not permit replications of either of the two full-scale prototype experiments presented next. Subchapter 5.1 presents the results that are relevant to RQ1 and RO1.

5.1.1 Prototype 1 – UR10

Prototype 1's main purpose was to perform preliminary robotic cleaning tests. Publication 2 (Bjorlykhaug et al., 2017) discusses the main features of this prototype. The lessons learned from this prototype were brought into the development of Prototype 2. In relation to the approach to classification by developed by Ullman (2010), which was presented in Chapter 2.2, the UR10 prototype was designed as a *proof-of-concept prototype*; it was designed to learn and determine how the requirements would come into play during operation in a physical environment. The virtual and physical prototypes are shown in Figure 5.1. For details regarding the mechanical design, the reader is adviced to A1 The Resulting Prototype 1 on page 79.

5.1.1.1 Cleaning System

The cleaning system for Prototype 1 consists of an industrial cleaning station, specifically a Voyager 4K mobile main station from System Cleaners (System Cleaners, 2019). These stations come with built-in compressors and are stand-alone mobile cleaning units. They can be used for rinsing, application of foam, and disinfection, and they only need an electrical connection and a connection to a water supply. The Voyager 4K has a 15-m hose attached with an end-mounting for different nozzles, which can be changed depending on the medium used (water, disinfectant, or foam). The hose and nozzle-holder are attached to the UR10 such that the nozzle is facing 90 degrees from the lance. The industrial cleaning system is supplied with water and electricity from Optimar’s shop floor.

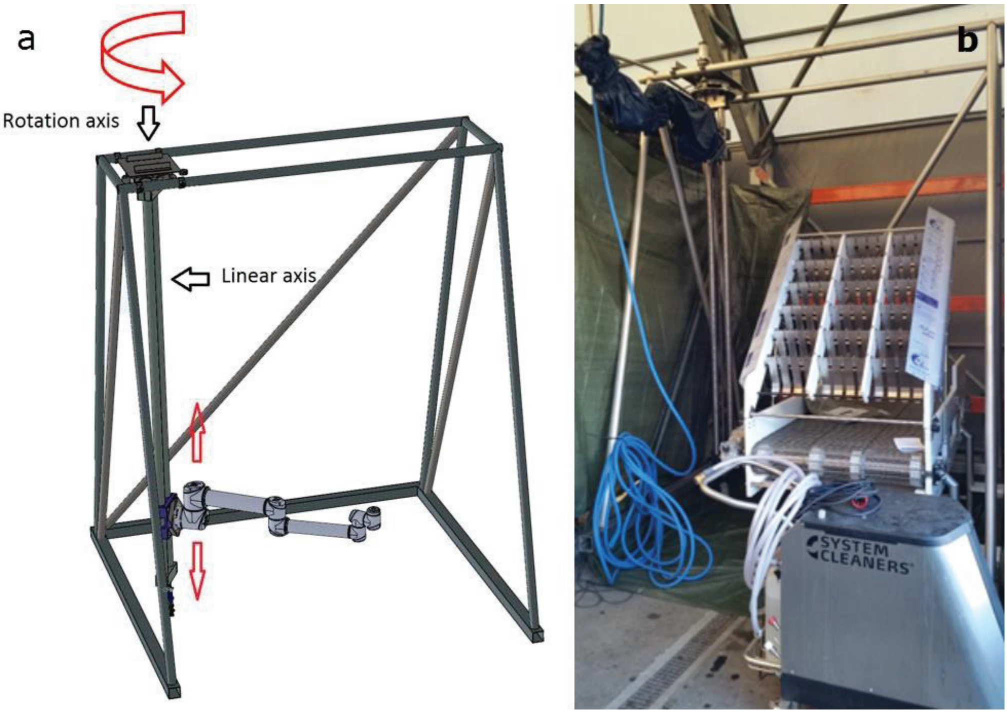

Figure 5.1 First prototype for testing. The virtual prototype is shown in a), and the physical prototype is shown in b).

For more details, such as those concerning the control loop for this prototype, the reader is referred to Paper 2 (E. Bjørlykhaug, Giske, Løvdal, Mork, & Egeland, 2017).

5.1.1.2 Lessons Learned

Several lessons were learned from the first tests of the robotic cleaning system: First, the proposed prototype featured insufficient reach. The UR10 had a suitable weight but was not appropriate for the cleaning task; in addition, the UR10 does not cope well with harsh environments, and, despite the efforts to increase the reach with the linear axis, the slewing ring, and the extra arm tooling (lance), this solution was not able to clean the entire electric stunner as the simulations said it would. This is partly due to the fact that determining the spray area is difficult in the simulation environment, and partly because orienting the nozzle correctly proved difficult in real life due to for example hose restrictions. This solution was determined not to fulfill the goal of cleaning an entire processing line, even when the reach was expanded by introducing an additional external axis, (i.e. a linear rail parallel to the ceiling). The results of this test are presented in Chapter 5.4.1.

After this cleaning test, it became evident that a more thorough replication of an FPP was needed to eliminate uncertainties regarding several of the requirements. Several flaws in the concept were also discovered, such as the inadequate flexibility of the end-of-arm tooling and the insufficient reach previously mentioned. While some could be fixed by modifying the concept, it became evident that an entirely new concept was needed develop a robotic cleaning system that would be suitable for industrial implementation and demonstrate the required performance. Prototype 1's adherence to the requirements is further addressed in Table A.1, which can be found in Chapter A3 Detailed Evaluation of Prototypes on page 83. The prototype's design and the cleaning design were considered to be satisfactory. The aim of the design and the experiment was to produce a proof-of-concept prototype to determine how the requirements would come into play in the physical world, which was fulfilled as learning outcomes.

5.1.2 Prototype 2 – Custom Solution

The second prototype is a custom-built robotic manipulator accompanied by a custom rail and trolley designed specifically for the task of robotic cleaning. For details regarding the mechanical design of the robot and auxiliary equipment, the reader is referred to A2 The Resulting Prototype 2 on page 79. It was manufactured inside the lab environment that was built for the purpose of testing the robotic cleaning systems developed during this research. This prototype fulfills several roles regarding the purpose of a milestone prototype presented by Ullman (2010) in Chapter 2.2. It is a *proof-of-product prototype*, and the geometry, materials, and manufacturing process are as important as the function of the prototype. It is also a *proof-of-process prototype*, as it was used to verify both the geometry and the manufacturing process. It was built with the exact materials and manufacturing processes that would be required for installation in an actual FPP, to make it possible to install in an FPP if possible.

This robot system design is well-suited for installation in several FPPs, as most of the components may be customized to fit each FPP's requirements. The circular beams used, for instance, can easily be made shorter or longer. As can be seen in Figure A.3 on page 81, Prototype 2 becomes quite compact when fully folded, meaning that it may be tucked out of the way when an FPP is performing regular fish processing. Figure A.4 on page 81 shows Prototype 2 fully at full extension. This figure shows that it is suitable for reaching large areas. This configuration also makes it nimble when compared to conventional industrial robots of comparable size/reach.

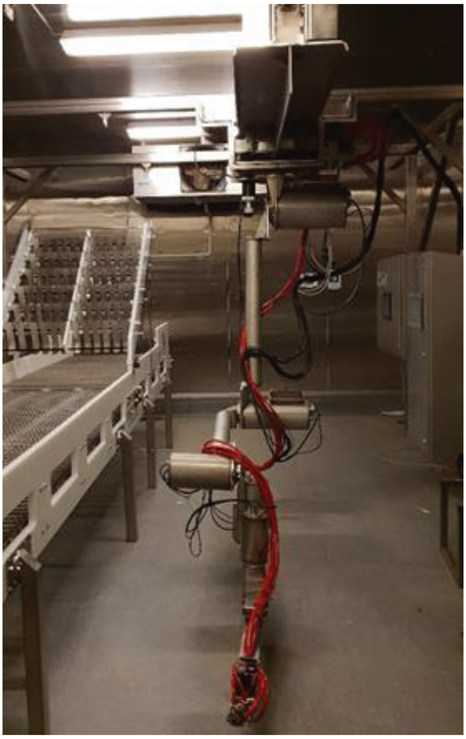

Figure 5.2 Finished Prototype 2.

5.1.2.1 Control System

While this section does not go into excessive detail regarding the control system, as it is beyond the scope of this thesis, it does present the main points.

As the manipulator is a customized solution, a specially designed control system was needed. An Omron PLC was used as the base element for the control system due to its prevalence in the industry and the fact that it is considered a stable component. This, however, led to challenges in implementing the kinematics and generating trajectories for the motions inside the PLC program. Programmable logic controllers often do not offer native support for matrices and the matrix operations that are needed for kinematics and trajectory generation. A stand-alone program for pre-calculating the trajectories and inverse kinematics was developed and executed on a PC running on Windows, hereafter referred to as the trajectory generator. The output of this program was fed to the PLC.

Visual Components was again used to simulate the movements of the manipulator and the trolley, and the kinematics of the manipulator were imported into VC. A macro was developed in VC to export the simulated motions into an appropriate format. Joint values corresponding to a desired pose, the value of the external axis and parameters for nozzle control, meaning information about which of the nozzles that should be active at any given time, are all exported from VC. All trajectory generation is done ahead of time and manually transferred to the PLC, as can be seen in Figure 5.3, which is adopted from (E. D. Bjørlykhaug, 2018).

For details concerning the specifics of the program and calculation of kinematics, the reader is referred to (E. D. Bjørlykhaug, 2018).

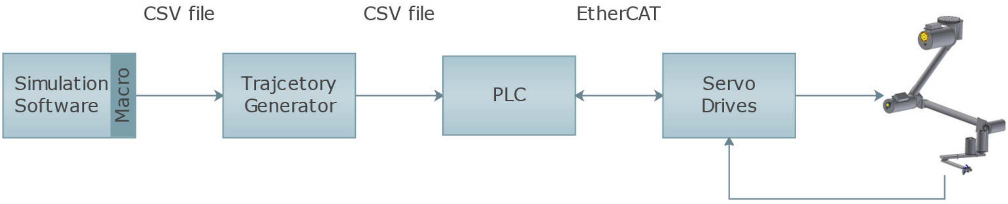

Figure 5.3 Control system for Prototype 2.

5.1.2.2 Comparison to Conventional Industrial Robots

The custom manipulator is compared to comparable conventional industrial robots in Table 1. As can be seen in the table, the most significant differences are in terms of weight and footprint. Properties such as accuracy and repeatability are omitted from the table, as they are not as important for cleaning purposes, but Prototype 2 scores lower on these properties. It is, however, considered an acceptable trade-off to achieve such a long reach with such a low weight.

Table 1 Comparison of mechanical properties for industrial robots and Prototype 2

Supplier	Model	Reach [mm]	Payload [kg]	Weight [kg]	Footprint [mm x mm]
KUKA	KR 30 L16-2	3102	16	700	850 x 850
FANUC	M-710iC/12L	3123	12	540	550 x 550
ABB	IRB 5500	2975	13	600	500 x 680
Prototype 2		≈ 3720	≈ 10	≈ 220	Ø 300

The lower footprint for Prototype 2 enables a smaller trolley and may thus reduce the weight of the trolley and thus that of the rail. In addition, a smaller trolley may facilitate a smaller turn radius.

5.1.2.3 Cleaning system

Six nozzles were mounted to the end effector of the manipulator at 45 ° apart, creating a spraying sector of 270 °. The nozzle arrangement is depicted in Figure 5.4. The nozzles are mounted on a base, which is a 3-mm AISI 304 plate that was cut and bent to allow this arrangement. The same industrial cleaning station as used for Prototype 1 is used to feed the nozzles with water and chemicals, and the feed from this station is split into six, with one individual flow per nozzle. The valves, which are presented in Figure A.6 on page 83, are controlled by the PLC in the robot's control system.

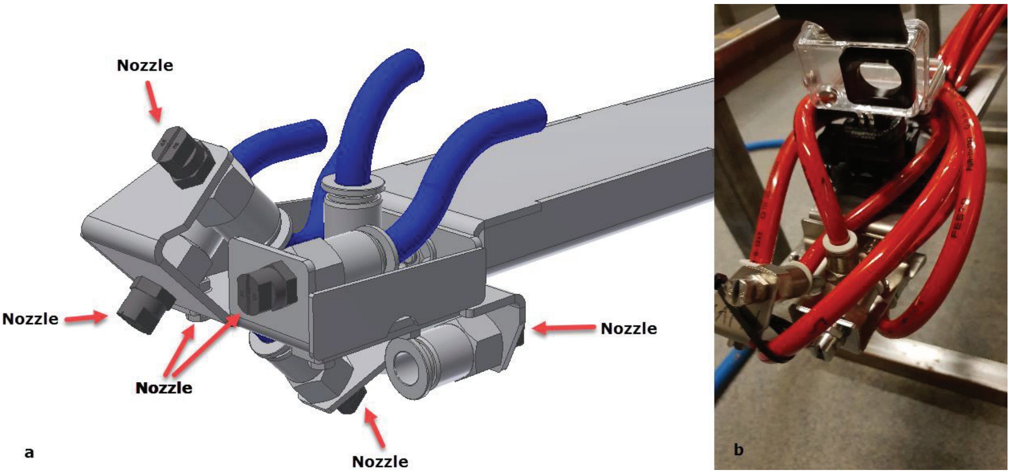

Figure 5.4 Nozzle arrangement, where a) shows the CAD model and b) the physical model. A GoPro was mounted on the physical model to capture video, as can be seen in b).

5.1.2.4 Lessons learned

Even though testing of Prototype 2 indicated that it fulfilled many of the requirements, it still led to another set of requirements, which will need to be addressed in future work regarding robotic cleaning of FPPs. These additional requirements were presented previously in Chapter 4.2 and in Table A.1 on page 83; these include requirements such as short installation and commissioning times and the need for a "push play" function for starting robotic cleaning.

During testing, the PLC program was tasked with logging the performance of each servo motor, and it was discovered that the motors were operating at about 20–30% of capacity with regard to torque. This indicates that it would be possible to slim the manipulator considerably, as the servo motors and gears are the main drivers of the weight of the system. For instance, the servo motor and gearbox in joint 2 weigh approximately 45 kg, while the same components in joint 6 weigh about 4 kg.

Prototype 2 had an issue with mechanical vibrations. The frequency of these vibrations is greatly influenced by the stiffness of the manipulator, and this should be considered carefully during the design of joints and links. In particular, the joints close to the base can impact the vibrations at the end effector to a significant degree. In Prototype 2, the trolley can be assigned some of the blame, as its spring suspensions were under-dimensioned. During this test, low accelerations for the end-effector movements were used to mitigate the problem to some extent, but the performance suffered because of this (especially with regard to speed). The cleaning results, which are presented in the following section, proved to be respectable, and the conclusion is that reach is more important than stiffness when performing cleaning procedures. Both the experimental design setup and prototype designs can be considered to be satisfactory, as the aim of the design was to produce a proof-of-product and a proof-of-process prototype with which to determine how the standard method of manufacturing equipment in the industry would fit the system and how well the proposed robotic cleaning device would perform the processes it was designed to do.

5.1.3 Evaluation of Prototypes

Product development focuses to a large extent on accommodating customer requirements, and thus it is very important to evaluate the requirements discussed in this thesis. In this regard, it is important to consider not only those requirements relating to the robots but also those associated with the surrounding processes, such as installation and commissioning.

Table 2 below represents a summary of the aspects and requirements discussed in Chapter 2 for each of the two prototypes. Some of the requirements have already been commented on in the articles which are found in the Appended Papers section on page 93. The table in the appendix, Table A.1 on page 83, represents the extent to which Prototypes 1 and 2 accommodate each of the requirements in further detail.

Table 2 Comparison of aspects of the two prototypes

Aspect/requirement of robotic cleaning	***Concerning Prototype 1***	***Concerning Prototype 2***
Cleaning quality - *Sufficient cleaning area and dexterity* - *Sufficient cleaning effectiveness*	Prototype 1 provided sufficient cleaning quality in the aspect of microbial removal. However, Prototype 1 did not have the adequate reach, or dexterity needed to be considered an acceptable solution.	Prototype 2 surpassed Prototype 1 with regards to both reachability and dexterity, as it was custom built for the task. It also performed well enough with regard to cleaning. There is still potential to increase the reach, which will be necessary for industrial acceptance.
Hygienic Design - *Intrinsic contamination* - *Chemical/environment tolerance*	Even with a raincoat, Prototype 1 is considered too fragile with regards to the environment and cleaning chemicals. Even though the robot itself has a clean design, the material choices make it unfit for the task.	Hygienic design principles are considered throughout the design of Prototype 2, and both materials and designs are capable of coping with the environment and the cleaning chemicals it will be exposed to. The risk of intrinsic contamination is considered low due to the design.
Stabilizing processes - *Repeatability and stable performance* - *Potential for improvements* - *Optimization of cleaning routine (chemicals, movements, cleaning tools)*	As a proper industrial robotic arm, Prototype 1 is well suited for creating a repeatable, stable cleaning process, and consequently improve said processes iteratively.	Prototype 2 is not an industrial robotic arm. However, it is built with robust industrial components (servo drives, PLC, servo motors, etc.). It is as such capable of repeating tasks as instructed the same way as an industrial robot. Robust components means that a stable process is possible to

		achieve, and later optimization of the cleaning process.
HSE - *Reduced chemical usage* - *Tough working conditions* - *Training* - *Human safety*	The UR10 robot is a collaborative robot and is well suited to work alongside humans. It has integrated security.	Throughout the design process, the processing environment and chemicals used in cleaning have been considered in Prototype 2's design and component choices. It is well suited for operation in these conditions.
	Both prototypes would require additional security in an industrial setting to ensure human safety, such as light gates or fences. It is believed that through stabilizing and optimization of processes, reduced chemical usage is achievable.	
Agile integration in FPPs - *Minimal obstruction* - *Short commissioning times* - *Retrofit* - *Small footprint* - *Low weight* - *Safety*	Due to the low weight and small footprint, a robot of Prototype 1's size is well suited for installation in an FPP. However, the infrastructure needed surrounding the UR10 to increase the reach would likely be intricate and would mean a lot of obstruction in the workplace and a problematic retrofit installation.	The arms of Prototype 2 are created with interfaces to the links between the arms. Thus, the robotic arm may be tailored to each FPP, and such is the case for the rail and trolley. It is believed that although complicated, by combining 3D-scanning and simulation, it is possible to achieve short commissioning times for the retrofit. The arm is relatively collapsible (see Figure A.3 on page 81) and should not obstruct routine production much. The rail also creates the possibility of placing the robot away from production. Compared to the reach, weight and footprint is relatively low.

On the basis of Prototype 2, further design advancements are needed before this system can be implemented in an FPP. The testing done in this work was conducted at low speed, partially because speed was not considered important and partly because a certain degree of stiffness lacked in the construction. Time and resources did not permit a second design to be tested, in which more thorough calculations on stiffness should be performed.

Other areas for improvement include reviewing the trolley and rail designs. The horizontal areas of the trolley and rail should be angled where possible. This will avoid build-up of potentially contaminated water on the rail. A method of cleaning the rail without risking contamination of already cleaned equipment below is also required.

Similarly, the robotic system itself must be cleaned to avoid it posing new contamination threats. This was partially addressed in this work through developing a hygienic design for the system, but it may be necessary to develop a cleaning system for the robot itself, possibly by developing its own garage or washing hall with an accompanying cleaning system. Such an approach should also dry the robot system such that it is completely dry when starting a new cleaning cycle. The aspect of hygienic design also relates to the protection of hoses and cables; as can be seen in Figure 5.2, the hoses and cables in Prototype 2 are visible and exposed. This would not have been accepted in FPPs, and, for their protection and to avoid bacterial build-up and make cleaning easier, hoses and cables should be shielded.

5.1.4 Prototype Lab

The lab environment consisted of two standard FPE machines that are present in most FPPs, both in Norway and in other countries, and on fishing vessels. The fish stunner and the gill-cutting conveyor are two components that it is critical to clean well, as they are typically situated early in the processing line; in particular, the gill-cutting conveyor is subject to exposure to fish blood, slime, protein, and residue (parts), which may contaminate other fish if not properly cleaned.

The test lab was of sufficient size to be able to test a full-sized robotic cleaning system and compare its performance to that of manual cleaning. The prototype lab transpired to be the perfect analog to an FPP. As explained in Chapter 4.1.2.1, it was situated in an FPP that had been decommissioned and was only used for storage. However, the lab enabled testing at a level that was much more realistic than would have been possible when testing at Optimar’s location, which is where Prototype 1 was tested.

A prototype should include both models of the product (the prototype) and of the real environment (the test environment) (Tronvoll et al., 2016). Additionally, more close-to-real testing increases the confidence level of test results. With the multi-domain challenges present for a robotic cleaning system (technological and biological), only two options would have provided sufficient answers to the research questions addressed in this work: 1) installation in an FPP or 2) thorough testing in an environment similar to the environment found in FPPs, which is what was done.

The prototype was used for an integration test, where the system is brought to its intended operating environment and tested, for example mounting and testing a prototype wing design on an aircraft (Ulrich & Eppinger, 2015). Consider Figure 5.5, which was adapted from (Tronvoll et al., 2016); it depicts the steps that were followed during this prototype test. Due to time and resource constraints, only one iteration was performed in this work, but several lessons were learned (experience) as an outcome of this activity.

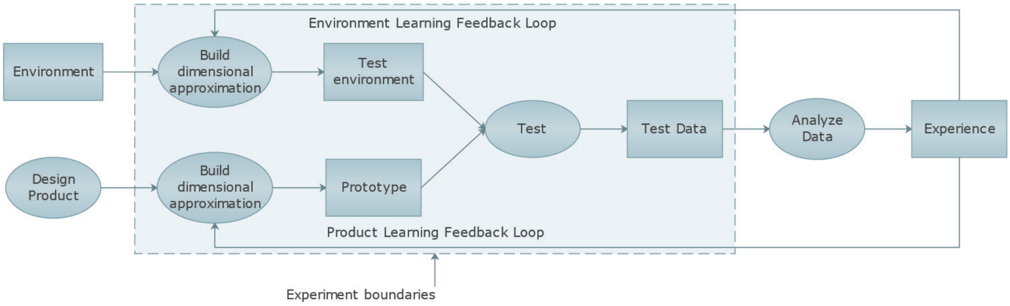

Figure 5.5 Extended design-build-test cycle (from (Tronvoll et al., 2016)).

The purpose of the experimentation done with Prototype 2 was to determine the performance of the cleaning procedure and the extent to which it satisfied the requirements, as well as the goodness of the processes associated with the prototype in terms of installation and commissioning. All of these aspects are difficult to evaluate without a near real-world test, which is why the prototype lab is important. The evaluation is done both with regard to testing the processes of installing and commissioning the robotic cleaning system by building an undocumented test set-up and with regard to being able to fully test the system using both water and chemicals, which would have been difficult in the regular production facilities of OEMs in general, not to mention that it would considerably disrupt regular production. It also made it possible to determine whether the process of implementing a robotic cleaning system in a real FPP was possible and how it could be done.

The inputs used and the outputs produced during this experiment are presented in Figure 5.6 below, in which they are related to the framework presented in Chapter 2.2, specifically Figure 2.3. Not all inputs and outputs are listed in this figure, as it is meant to serve as an illustration of how the experiments conducted with Prototype 2 used both inputs and produced outputs concerning several characteristics.

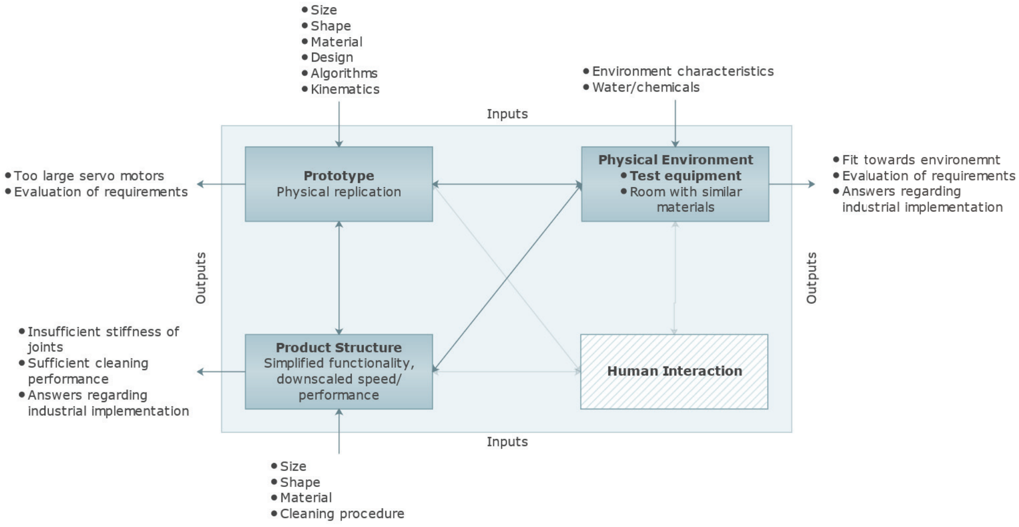

Figure 5.6 Prototype 2 experiment characteristics.

Human Interaction: Human interaction is disregarded, as no properties of human behavior were considered when examining the functionality and performance of the robotic cleaning system in this research. The manual cleaning operation, which is used for comparison, had no direct impact on the experiment with the robotic cleaning system.

Product System: In this case, this system was comprised of the test equipment, namely the electric stunner and the gill-cutting conveyor, in addition to the frame in which the prototype is suspended. This means that additional product structure beyond the robotic system itself was part of the *product system*.

Physical Environment: Aspects of the physical environment, such as environmental loads and characteristics, do not fall into any of the previous categories. The room itself is part of the system, which includes the environment created by the prototype during testing (e.g. spray fog and humidity).

5.2 Virtual Factory Layouts and Prototyping

Two papers (4 and 5) address the use of prototypes and virtual factory layouts in prototyping activities. The main results from these papers are presented in the following section, which provides the answers to RQ1, RO2, and RO3.

5.2.1 3D Scanning as Visualization Support in Prototyping and Planning

Three-dimensional scanning technology is shown to have great potential for supporting activities related to layout planning in FPPs. Two case studies were performed to evaluate 3D scanning as a form of visualization support. For a detailed explanation of the framework used, the reader is referred to Publication 4 (Lars Andre Langøyli Giske, Benjaminsen, Mork, et al., 2019).

5.2.1.1 Case 1 – 3D Simulation

By sing meshing operations and subsequent typical CAD operations, the point cloud was converted into solids, which are used in a simulation environment (see Publication 4 (Lars Andre Langøyli Giske, Benjaminsen, Mork, et al., 2019).). These were used to create the robotic cleaning paths (i.e. to program the robot). This reduced the number of iterations required to obtain a robot trajectory that covered all of the equipment in the cleaning test. The simulation program was also used for performing collision checks and further to avoid collisions, as there were differences between the virtual and the physical models of the robot manipulator.

5.2.1.2 Case 2 – Retrofit

The second case study for 3D scanning as a visualization support tool is a real industry project in which a part of an existing FPP was to be replaced with new equipment. The layout was also planned to be altered slightly. This is a typical retrofit project in the aquaculture industry. The following features were found, and are considered, to be important for a virtual factory layout to be used to plan a retrofit installation:

Table 3 Features related to a virtual factory layout for retrofit

Level of Development	Level of Accuracy	Level of Recognizability
As is Measurable 3D and 2D distances Measurable footprint	Coarse in general Finer in interfaces	3D block Shapes and features highly significant for object and specific objects

The VFL features mentioned in Table 3 above enabled use of the point cloud as a virtual tool with which to check the planned installation with respect to existing infrastructure and equipment. This required less accuracy than the previous simulation case, but still required some degree of accuracy where new equipment is planned to have interfaces with existing equipment. It was required that the point cloud be able to take measurements and evaluate footprints; in addition, it was considered necessary that it be able to recognize equipment (however, in less detail than for the simulation case). Since the retrofit needed interfaces to existing equipment, a level of recognizability in which where specific objects are recognized and measurable was needed. In Figure 5.7 below, the planned factory CAD layout was overlaid on a 3D scan of the factory. The different scan positions are shown as rectangles containing images. The surrounding building infrastructure was constructed from 2D layouts, while the grey "cloudy" area is the compound point cloud.

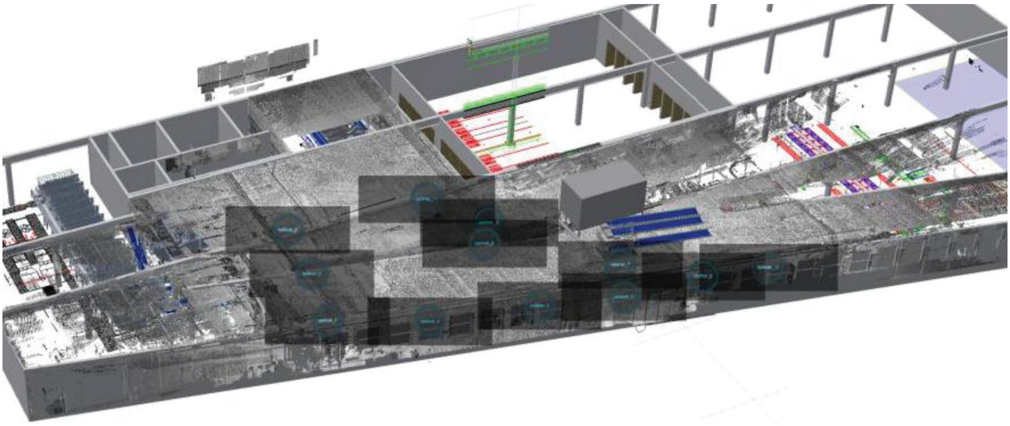

Figure 5.7 3D scan overlaid on a CAD layout.

Several errors were discovered when analyzing this overall model, one of which by Optimar's estimates allowed the company to avoid a four-week delay in installation time. The same method proposed and utilized by (Berglund et al., 2016), presented in Figure 5.8 below, was utilized to assess the layout with the point cloud overlaid on the CAD layout. The models and the end products (i.e. the equipment produced) were adjusted accordingly, as this is more practical than changing the reality in (i.e. the infrastructure of) the FPP.

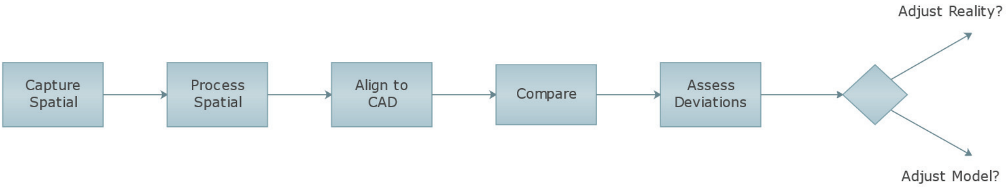

Figure 5.8 Method and framework for assessing a hybrid model (Berglund et al., 2016).

5.2.2 3D Simulation as a Virtual Tool for Prototyping

Figure 4.2 presents the impact of 3D scanning and simulation on the PD process. The typical case is that a simulation is used to fine-tune existing processing lines or for planning production lines. Three-dimensional simulation enables testing of complex equipment before it is built and making adjustments and refinements using virtual tools. By observing both the movements and data gained from the simulation, the prototype could be verified, validated, and reflected upon (see Figure 2.4). This allowed many useful insights to be obtained before the prototype was further tested in various 3D iterations (both designs and simulations) and eventually. This enabled shorter development cycles for the robotic cleaning system compared to building several physical prototypes and contributed to weeding out design errors at an early stage. For detailed descriptions of the study and its results, the reader is referred to Publication 5 (Lars Andre Langøyli Giske, Benjaminsen, & Mork, 2019).

Virtual prototyping is typically used to facilitate communication and to reduce costs by identifying errors (Camburn et al., 2017). With regard to the fish industry and prototyping efforts within it, simulation reduces the number of iterations when compared to those generally required to commission complex systems in existing plants (Hoffmann et al., 2010). It is stated in the literature that the risk of contamination increases with the amount of time and the number of times that workers intrude in food processing facilities (European Hygienic Engineering & Design Group (EHEDG), 2018; Moerman & Wouters, 2016b). This work shows that a reduction in the costs and time associated with prototyping can also be achieved by utilizing virtual prototyping and simulation. In addition, it is further believed that virtual prototyping may aid in reducing the amount of time and number of times that facilities must be accessed during both the planning and the commissioning of products and thus reduce the risk of bacterial contamination.

As stated by Erichsen, Wulvik, Steinert, and Welo (2019), research on prototyping is often done retrospectively. The same authors developed a small rig for capturing the data (documentation) of small-scale, low-fidelity prototypes in an article titled "Digitally Capturing Physical Prototypes During Early-stage Product Development Projects for Analysis" (Erichsen, Sjöman, Steinert, & Welo, 2019). In the project discussed in this thesis, the 3D scan of the test room with the prototype of the cleaning robot installed served to provide complete documentation of a full-scale, high-fidelity prototype.

In this work, both 3D scanning and 3D simulation were utilized in prototyping, and these tools are considered to have significant potential in terms of achieving a greater competitive advantage during PD activities. The utilization of these tools in this project resulted in increased effectiveness and efficiency and enabled a faster introduction of advanced prototypes, which cost less to bring to fruition than would a conventional physical prototype with the same advanced capabilities.

3D scanning and 3D simulation may even impact other research areas. Design for environment (DfE) is defined by Bakker (1995) as the "development of products by applying environmental criteria aimed at the reduction of the environmental impacts along the stages of the product life cycle." The tools and methods that have been developed within the field of DfE are rarely used by designers in the industry due to a lack of time and the fact that many of these approaches are perceived as lacking usefulness in an everyday work environment (Lindahl, 2005). Simulation and 3D scanning may, in the context of designing FPE and plants, be regarded as DfE tools and methods, as they serve to reduce environmental loads through reducing the need for rework proposed solutions and make it possible to engage more in the virtual development of both products and processing lines.

5.2.3 Industrial Implementation

The previously presented results are important in terms of achieving the industrial implementation of a robotic cleaning system. A streamlined method for obtaining accurate and up-to-date spatial data concerning FPPs and converting this data to solids for use in a simulation environment will be the preferred working approach. Such a method will enable short installation and commissioning times, which is a crucial factor in achieving industrial performance in the aquaculture industry.

The scanned data can serve as the starting point for planning an installation and enable customization of a robotic cleaning system to ensure that it will fit in an FPP. It became evident during this work that the use of 3D scanning to create documentation and further to use the data obtained to develop reverse-engineered CAD models is possible, and that such reconstruction has satisfying outcomes. The entire process is very time-consuming, and highly specialized skill is necessary, confirming previous results obtained in (Volpe et al., 2017). The end result is influenced by the designer's capabilities and confidence with the tools used for this process.

The simulation environment can be used to create robot trajectories for cleaning, which can be modified and improved through several iterations. Simulating these trajectories can also reveal design errors and aid in their elimination prior to installation. Commissioning times will thus be shorter when compared to online programming and traditional approaches to installation and commissioning, as the cleaning program will have been developed beforehand. It is nevertheless expected that some in-place adjustments will be necessary to ensure a smooth robotic cleaning program. The results obtained and presented from 3D scans and simulations with regard to installation and commissioning times will also prove important for FPPs and their throughput of fish by enabling less downtime for the FPPs. The perspective of installation and commissioning is also important for the business side of the company providing the robotic cleaning solution. Without the ability to quickly install and commission a robotic cleaning system in existing processing plants, there will likely not be sold enough systems to make the concept economically viable.

Optimar AS has already implemented the use of 3D scanning as a tool in the industry on the basis of this project. As explained in Chapter 5.2.1.2, it is an excellent tool for retrofitting equipment into existing FPPs. Both the test lab and the previously discussed retrofit project allowed thorough testing of 3D scanning, and the technology is now implemented in live projects. The use of 3D scanning in project processes is illustrated in Figure 5.9. There is a one-to-one replacement of time use of using 3D scanning for taking measurements for planning during the sales phase when compared to traditional measurement techniques. The extra day used for 3D scanning to obtain as-built documentation for utilization during the service and aftermarket phase is seen as an acceptable trade-off when compared to not obtaining documentation of the small changes that usually occur during installation and commissioning.

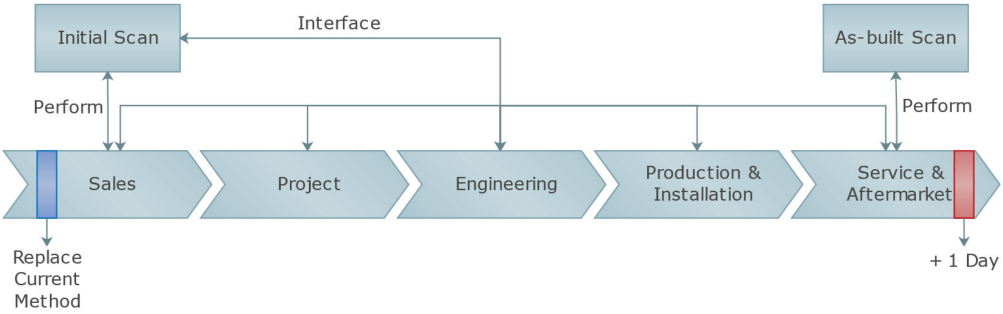

Figure 5.9 Added time required due to the implementation of 3D scanning into processes.

An added benefit of utilizing both 3D scanning and simulation is the reduction of installation time at FPPs, which is beneficial for bacterial mitigation and the reduction of contamination risk. Three-dimensional scanning and simulation may even be expanded into hygienic design tools in the future.

5.3 Hygienic Design – Design for Cleaning

The results presented in this section answer RQ3 and RO4, which are related to hygienic design, as well as design for cleaning. For more detailed information on the approach to hygienic design measures adopted in this study, the reader is referred to Publication 3 (Lars Andre Langoeyli Giske et al., 2017). Hygienic design and design for cleaning are two sides of the same strategy, namely utilizing the design of components, products, and systems to mitigate bacterial risk. One strategy is to implement design measures that reduce the risk of bacterial growth, such as avoiding cracks. Another strategy is to take into consideration accessibility for cleaning when designing machines or plants, for instance by avoiding areas that are hard to reach or require disassembly to be cleaned. These two strategies should be combined to maximize cleaning performance.

Design for cleaning concepts may introduce higher production costs, but, in compensation, OEMs will be able to charge FPPs a higher price for their products due to reduced cleaning times and less risk of bacterial contamination. Furthermore, the disassembly of equipment with the purpose of cleaning it is time-consuming and requires skilled personnel. An FPP is likely to save costs related to disassembly during cleaning if the equipment is designed with cleaning in mind and does not require disassembly operations to be thoroughly cleaned.

There have also been developments that reach beyond the scope of the presented article. In order to avoid the ingress of water in pipes used for construction frames and similar in equipment, the industry has adapted round bars instead of closed tubes. By using round bars as the profiles of choice in some equipment’s framework, for example, conveyors, which leads to very open and cleanable designs; Figure 5.10 presents an example of this. Such an approach eliminates the contamination threat of closed profiles altogether. Open profiles, such as those depicted in Publication 3 (Lars Andre Langoeyli Giske et al., 2017), are also very effective in terms of eliminating bacterial build-up due to the ingress of contaminated water or blood. It has been found, however, that they could result in backsplashes of water on the cleaners, which is undesirable from a health, safety, and environmental standpoint. Also, they may result in splashing onto surrounding equipment, which can cause cross-contamination. Removing as many horizontal surfaces/areas where potentially contaminated water is left to dry is a hygienic design principle that can be fulfilled by, for example, using round tubes or open profiles instead of square tubes.

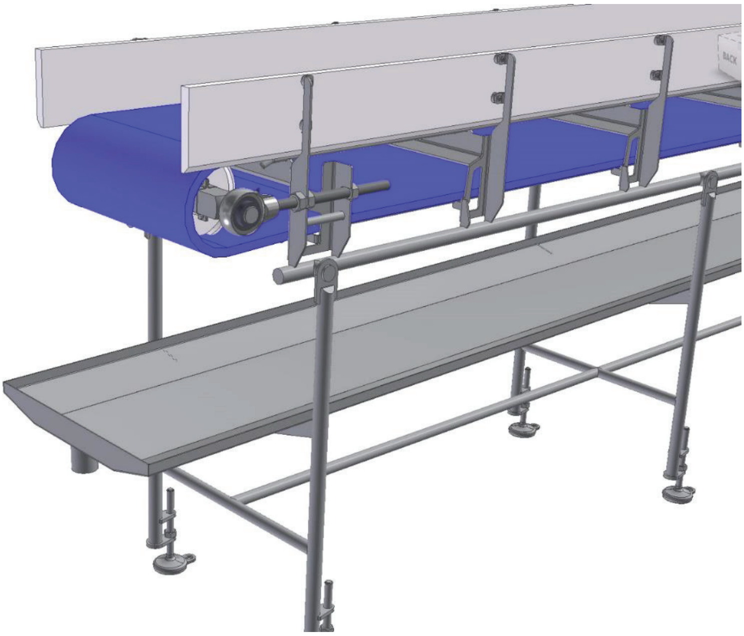

Figure 5.10 Solid steel bar conveyor.

It was also attempted to apply design for cleaning principles to the custom robotic cleaning system developed for experiment 2. This system was built with round tubes and as few crevices as possible. The interface between the tubes and the end plates for mounting is shielded with gaskets to avoid intrusion of water; which was done both from a design for cleaning perspective and from a protection of electronics perspective. Servo motors are covered to avoid bacterial build-up in their external geometry, which is filled with cracks, crevices, and confined spaces. The two links operating in the horizontal space have horizontal surfaces and should be redesigned to better conform to hygienic design principles.

Design for environment (DfE) is an important aspect of the sustainability of the NAI (Bar, 2014). Hygienic design – design for cleaning is important in DfE, as can be seen by comparing the machine attributes identified in (Bar, 2014). The machine attributes in terms of DfE are presented in Table 4 below:

Table 4 Environmental design guidelines for FPE (adapted from (Bar, 2014))

Machine attributes	*Design guidelines*
Cleaning	• Reduce need for washing agents and disinfectant • Design for cleanability • FPE should be easy to dismantle • Reduce contact points between equipment and product to avoid contamination • Smooth nonstick surfaces for easy transportation of product and residue away from the machine • Minimize food-grade water consumption

Material selection	• Materials that are easy to clean • Recyclable materials and pure material fractions • Durable
Assembly/Disassembly	• Easy to disassemble; in particular, care should be taken of parts that needs to be changed frequently, such as conveyors

In relation to assembly/disassembly, it has been suggested in this thesis that welding is the preferred method of joining parts. This still holds true despite the fact that it violates the findings presented in Table 4, as only components that are regarded as spare parts should be available for disassembly. It is a finding of this work that welding parts together, in general, reduces bacteria build-up, which reduces the cleaning required and thus increases the sustainability of FPE.

5.4 Robotic Cleaning of Fish Processing Plants

Two experiments evaluating the effectiveness of robotic cleaning were performed, with increasing attention being paid to the industrial implementation of the robotic cleaning solution. The cleaning experiments made it possible to provide an answer to the overall research objective of how robotic cleaning may increase the effectiveness of cleaning in FPPs. In both experiments, Nofima assisted with the bacteria mix and the inoculation, sampling, and growing of the bacteria, in addition to the evaluation of the cleaning results.

5.4.1 Cleaning Experiment with Prototype 1

The robot was programmed manually through its teach-pendant by manually guiding the industrial manipulator to each point in a zigzag cleaning pattern. Efforts were made to keep the distance from the nozzle to the equipment approximately 20 cm, a typical distance for cleaning in the industryThis experiment was performed without comparison to manual cleaning; however, the cleaning results were promising. The reader is advised to consult Publication 2 (Bjorlykhaug et al., 2017) for a detailed description of the microbiological analysis conducted during this experiment. For some of the control points, the bacteria count was close to the detection limit of 0,5–1 log cfu/cm^2. The cleaning results for experiment 1 are presented in Publication 2 (Bjorlykhaug et al., 2017).

In addition, the prototype provided valuable insights into how to accomplish the robotic cleaning of FPPs. A brief overview of these results, which were previously presented in Chapter 4.2 and discussed in Table 2 and Table A.1 on pages 49 and 83, respectively, are presented below.

- Greater reach of the manipulator was needed;
- The robot was not suited to the task;
- A better and faster method of programming the robot was needed;
- The weight and footprint of the robot were well-suited to the task; and
- Nozzles and end-effectors may play a crucial role in determining how well a robot will clean.

5.4.2 Cleaning Experiment with Prototype 2

After the first cleaning experiment, it was decided that a more sophisticated solution was needed, and a second experiment was developed featuring a completely new solution based on industry-standard equipment and a custom-built robotic cleaning system (see Figure 5.11). In cleaning experiment 2, the customized robot cleaning system was compared to the manual cleaning to evaluate the performance of robotic cleaning. The manual cleaning operator had 15 years of prior experience as a cleaner in an FPP and was instructed to clean the equipment as if it were situated at his normal workplace. Only the cleaning performance, not the cleaning time, was the focus of this test. The cleaning time is presented in Table 5 below.

Table 5 Cleaning time comparison in experiment 2. Time in minutes.

Procedure	Rinse	Soap	Wait	Rinse	Disinfectant	Wait	Rinse	Total time [min]
Manual	6	2	10	10	1,5	10	5,5	45
Robotic	33	33	10	33	33	10	33	185

Cleaning was performed in the exact same way both times, following the industry-standard procedure presented in Chapter 3. Steps 1, 2, 3, and 4 were not necessary owing to the non-existence of fish debris and the absence of electrical equipment. Disassembly was also not required. The only difference between manual and robotic cleaning is the spraying path and the fact that the nozzle(s) are situated either in the hands of the operator or at the tool center point of the robot.

The cleaning results show a significant reduction in bacteria count compared to manual cleaning, see Figure 5.12. For a microbiological analysis, the reader is referred to Publication 1 (Lars Andre Langøyli Giske, Bjørlykhaug, et al., 2019). As can be seen from Table 5, the custom robot used significantly more time than the manual cleaner. Time is not considered important in this project, but a robot should clean the same equipment and area in the same time as a manual cleaner (or less). This time difference is due to the fact that the robot was not optimized with regard to stiffness; in addition, the servo motors had to be run at a slow pace compared to what was theoretically possible. The time difference does not matter with regard to bacterial removal, as the desired effect from the cleaning aid is typically reached before the recommended waiting time (Lilleborg, personal communication). The time difference is therefore neglected when discussing the cleaning results.

The robot trajectories in the first and only robotic cleaning system test performed in full scale were not optimized with regard to industrial cleaning. The trajectories were instead established through trial and error by replicating the manual cleaning movements, with an emphasis on covering the entire processing line used in the experiment. The same pre-defined robot trajectory from the offline programming was used for all of the steps in the robotic cleaning process. There is a considerable potential for time savings, but this was not part of the study. In the future, it may well be that a robotic cleaning system may operate in entirely different ways, such as an “intelligent” cleaning pattern based on machine learning, once more research on robotic cleaning is available. Such research could enable a robotic cleaning solution with adaption and decision-making capabilities with regards to cleaning paths and evaluating cleaning quality.

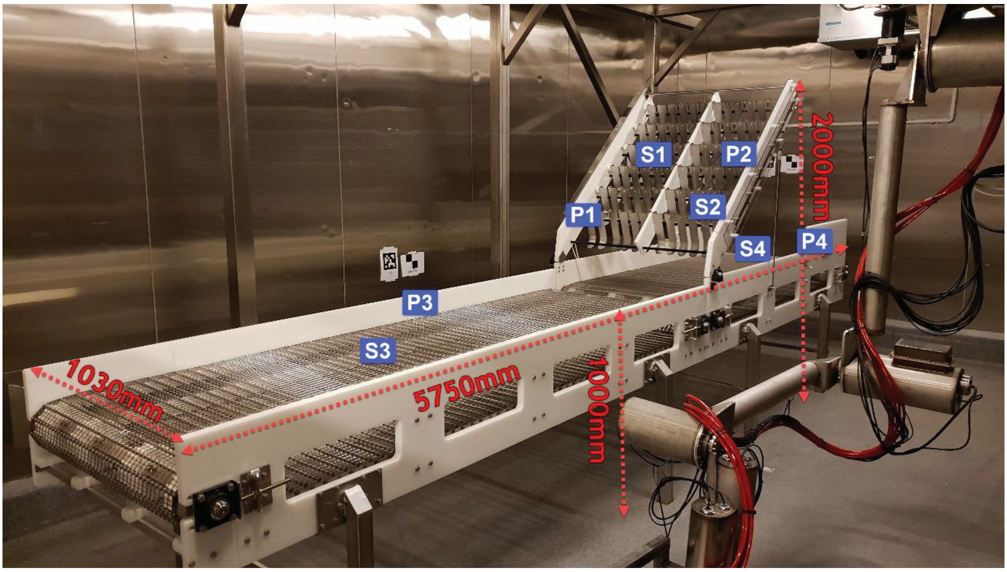

Figure 5.11 Dimensions and sample points of the test equipment used in experiment 2.

It can be seen from Figure 5.12 below that, in sample called *Plastic 4 Conveyor*, the manual cleaning removed more bacteria than the robotic cleaning. This, however, is not deemed significant for the overall comparison between robotic and manual cleaning, as there is some variation in the effectiveness from point to point, and this variation is the same both for manual and robotic cleaning. This variation may be due to the reach of the robot or the fact that the cleaning path was not optimized thoroughly in this part of the cleaning procedure. During potential real-life installations, this may be the case as well.

A way to mitigate this could be to develop vision systems, which are discussed in Chapter 6.5 on page 65. Furthermore, even though much emphasis has been placed on the use of simulation and offline programming to reduce commissioning time, it is not unthinkable that a short period (e. g. two or three cleaning runs) of fine-tuning the cleaning paths will be necessary, even though the simulation should attempt to offer as complete a cleaning path as possible even before installation. Unfortunately, testing the effectiveness of cleaning in running FPPs is difficult without running fish production (unless an FPP chooses to perform a robotic cleaning test in the same manner as done in this project, which is an unlikely scenario). This means that the fine-tuning and elimination of potential errors must take place in running FPPs. Methods for rapidly testing bacteria levels will be needed for this iterative fine-tuning process, and critical sampling points must be determined beforehand. It may also be possible to program the robot to take samples of bacteria levels at such points in the future.

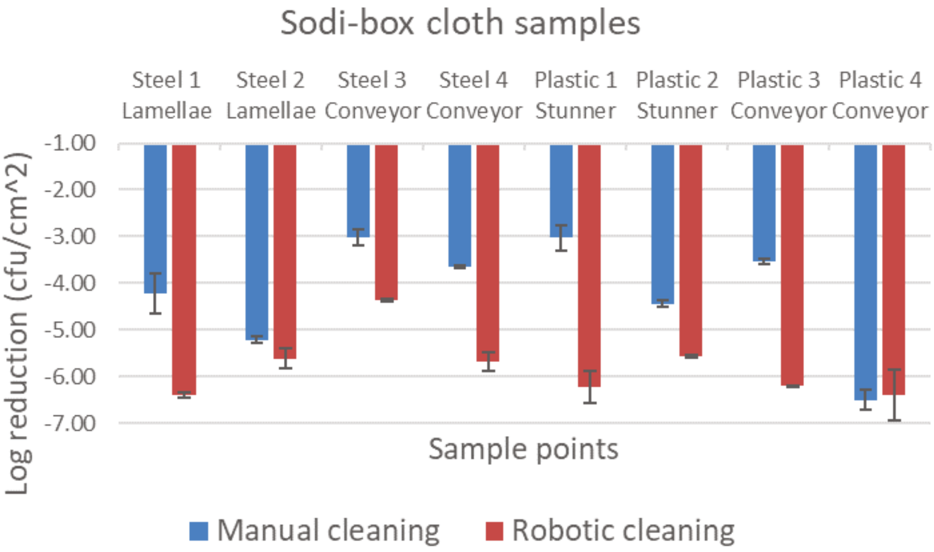

Figure 5.12 Cleaning results from experiment 2.This figure shows the reduction of bacteria count between both inoculated and cleaned processing equipment when using both manual and robotic cleaning.

During this research work, only one cleaning test with bacterial removal was performed. It would have been beneficial to perform several such tests to obtain more data; however, time and resources did not permit it. It was in addition a smaller research objective in the linked research project to look at reduction of chemical and water usage. Due to the demanding development of Prototype 2, with the accompanying technologies, getting this prototype to perform cleaning was prioritized. The robotic cleaning system was consequently not optimized sufficiently to make a fair comparison of either water consumption or cleaning time in the performed test, as the focus was to investigate cleaning quality, e.g., how well cleaned the equipment was after testing. It is, however, important to recognize that over time, robotic cleaning could lead to accurate data regarding chemical and water usage. Specifically, such a test setup should have two parallel production lines; one processing line with a robotic cleaning system and one processing line which is cleaned by traditional manual methods. In order to get an accurate comparison of water consumption (and in reality, both cleaning time and cleaning quality, plus chemical consumption), more long-term testing in an actual FPP is needed. This comparative test would allow optimization of cleaning paths, which eventually could be done by the system itself through introducing sensors, vision capabilities, and machine learning algorithms. The data from such a test could provide valuable insights into how a reduction in chemical and water usage could be obtained, for example through optimizing robot cleaning trajectories and nozzles. The test would also answer the effectiveness of cleaning with a robot versus manual workers better.

Even though the prototype lab discussed in 5.1.4 enabled close to real world testing, the true performance of a robotic cleaning system will not be disclosed until a prototype is installed and commissioned in an FPP. It is predicted that previously unforeseen challenges would arise during such an endeavor; however, the tools and methods discussed in this research work show that implementing robotic cleaning of FPPs is possible.

6 Conclusions

The conclusions to this work, which are presented in this chapter, are drawn from the results and the and the processes that were engaged in in order to achieve these results. The conclusions are presented in the same manner as the results (e.g. following Figure 1.3, which links the different focal areas to the research questions and research objectives). In addition, considerations regarding future work within the field of robotic cleaning of FPPs are presented at the end of this chapter.

The main conclusion, which this thesis verifies, is that the robotic cleaning system can deliver satisfactory industrial cleaning results. This system may be realized in the industry through the application of design and virtual tool for enabling efficient implementation of robotic systems in FPPs.

6.1 Robotic Cleaning of Fish Processing Plants

It is natural to pick low-hanging fruits first, which is why automating new processes becomes increasingly difficult for each new task or process that is automated. This thesis illustrates this challenge and provides new knowledge concerning how to automate a difficult process. The main objective formulated in Chapter 1.3 is repeated below for the reader’s convenience:

“*Exploration of how fish processing plants may be cleaned more effectively through the use of robotics*”

Based on the research project, the answer to this objective is complex and multi-faceted. However, the main conclusion of the work presented in this thesis is that the robotic cleaning of FPPs is feasible based on the results obtained from the two prototype tests. Prototype 2 cleaned as well as or better than manual cleaning. The potential for a more repeatable cleaning process possessed by a robotic cleaning system compared to manual cleaning is seen as one of the greatest advantages of robotic cleaning. Such a standardization of this process will allow for continuous improvement of the cleaning process, and the result will be better hygiene and control of bacteria in FPPs and, consequently, safer production of food. The training of human operators for manual cleaning operations will no longer be necessary; instead, the training of operators will shift to teaching them more about how to utilize the robotic system for better cleaning and how cleaning performance can be controlled and improved. The time they are required to work with chemicals, and during the night the will be reduced and consequently, the working conditions for the cleaners could improve. The potential advantages for FPPs are foreseen to be more sustainable and safer production, a reduction in the overall need for manual labor, and shorter cleaning cycles during nighttime, in addition to improving the overall hygiene of processing operations by reducing bacterial risk and eliminating tasks associated with heavy manual workloads. Introducing robots and automation into production facilities has generally been linked to lower production costs and the overall need for manual labor (International Federation of Robotics, 2018); thus, lower production costs are also seen as a potential advantage of robotic cleaning. Through further advancements of a robotic cleaning system through better control and optimization of water and chemical usage, a robotic cleaning system may aid in a more sustainable production of fish as well. Further optimization of cleaning paths could potentially also shorten cleaning cycle times.

6.2 Robotic Cleaning System

Fish processing plants may be cleaned more efficiently when using robotics and adhering to the requirements presented in Chapter 4.2 and in Table 2 and Table A.1. These include, but are not limited to, building a scalable and flexible robotic solution with a long reach and good maneuverability. The solution must account for varying plant layouts and must adhere to hygienic design guidelines.

The proposed custom robotic cleaning system, Prototype 2, is configurable and scalable in size and could accommodate several existing plant layouts while also satisfying hygienic design requirements. It is thus reasonable to conclude that this system is currently the best option in terms of achieving robotic cleaning of FPPs. Robot manipulators from conventional robot manufacturers may however be suitable as part of a robotic cleaning solution of new FPPs in the future. Such robots can be included in the initial design phase of a new FPP, and the facility’s infrastructure, equipment, and layout can thus be adapted to accommodate the use of such conventional robots as part of a cleaning solution.

It is difficult to conclude that the robotic cleaning system presented in this thesis represents the optimal solution for robotic cleaning of FPPs. However, it is rational to conclude that a custom-built system designed specifically for this purpose is required, as no system that would be viable for installation in FPPs currently exists.

However, although the project presented in this thesis shows that the robotic cleaning of FPPs is possible, the proposed system will not ready for industry implementation until further industrialization efforts are made.

6.3 Virtual Factory Layouts and Prototyping

It has been established in the literature that the degree of automation in the food producing sector is low; this is often due to the fact that automating processes involving biological material is more difficult than automating processes involving, for example, metal pieces, and there is a significant difference between achieving robotic welding and robotic cleaning. The difficulty of automating processes is also illustrated in this thesis, where several obstacles, including a lack of accurate spatial data and installation and commissioning challenges, had to be solved to achieve the goal of robotic cleaning.

Three-dimensional scanning represented one of the solutions used to overcome the issues identified above and may be used as visualization support both in the planning phases of a project and for creating simulation environments for manufacturing simulation, as was done for Prototype 2. There is a potential for the technology to serve as a learning and cooperation facilitator for the larger cluster of involved stakeholders for aquaculture engineering projects. It may be concluded that 3D scanning is a valuable tool for mitigating bacterial risk in FPPs through faster spatial data acquisition, increased understanding, reduction of errors and faster installation and commissioning time, which also benefits bacterial risk.

In the work done during this project, 3D simulation was utilized extensively in prototyping and testing activities. The capability to perform simulation enabled fewer iterations for developing the physical robot model and for developing a complete cleaning path, and thus faster commissioning. Based on this work it may be concluded that it is possible to use 3D simulation as a prototyping tool. The use of DES is novel in the NAI, but this thesis shows that it may be a valuable tool in terms of reducing the time and costs associated with PD, as well as in reducing commissioning time and consequently reducing the risk of contamination.

The combination of 3D scanning with 3D simulation further enabled rapid PD efforts at lower cost and led to a better end product (Prototype 2) in this case. This is likely to be valid for other complex PD projects as well. Both technologies are perceived as tools that can potentially contribute to the overall goal of safe food production.

Another finding of this research is that even though virtual (analytical) prototypes are a good replication of the real world and are consistently improving, replicating a virtual environment which is good enough that it replaces actual real-world testing is still difficult. One of the main benefits of building an actual test environment is the added possibility of evaluating a prototype in an environment that replicates the intended operating environment, which proved to be necessary to overcome the variety and mix of microbiological and technological challenges related to robotic cleaning.

6.4 Hygienic Design - Design for Cleaning

Design for cleaning principles are important to incorporate into product designs in the aquaculture industry in order to reduce the risk of bacterial contamination. Hard-to-reach or hidden areas that are difficult to clean or areas where water can accumulate after cleaning pose the greatest threats. Minimizing these areas is a central aspect of design for cleaning. A good design with regard to cleaning helps to minimize cleaning costs by reducing cleaning time and chemical and water usage, and such a design should not require disassembly operations to be cleaned. A robotic cleaning solution must adhere to these same principles to avoid the introduction of new risks with regard to bacterial contamination. A combination of robotic cleaning and good hygienic design has the potential to result in significant cleaning savings and reduced bacteriological risk. Bacteria such as *L. monocytogenes* are ubiquitous and may be introduced from different sources. Designing processing machines and equipment with the aim of minimizing bacterial colonization and enabling sufficient cleanability is of the utmost importance. Hygienic design should be a major focus even when planning facilities, not only at the component level but also on the larger system and facility levels.

6.5 Future Research Involving Robotic Cleaning

There are many aspects of the robotic cleaning of FPPs that could be considered as important to investigate in the future, and these opportunities exist in many different research fields. A brief overview of the future research needed in relation to the subjects of this thesis is presented in the following paragraphs.

The origin of bacterial contamination and the vectors and environmental factors that control the spread and establishment of pathogens are not well-known. Accurate detection of biofilm and/or bacteria could be a major contribution to safe fish production. Even though humans are among the species with the best eyesight and have incredible capabilities with regard to clearly capturing the 3D world (Caves, Brandley, & Johnsen, 2018), we are not suited to identifying inadequate cleaning on a bacteriological level. The current methods for measuring cleaning effectiveness in FPPs are either fast but do not detect specific bacteria or require resources and time to collect and cultivate samples.

Faster specific methods, such as PCR, are not dependent on cultivation, but these also require substantial manual labor or potentially expensive automated systems, chemicals and reagents for processing samples, and the isolation of high-quality DNA. Despite the fact that FPPs are cleaned on a daily basis as a precaution, attempts to combat bacterial contamination are ultimately still reactive, as they occur after detection of bacteria, as opposed to being preventive, not unlike corrective maintenance versus preventive maintenance. Industry 4.0 tools such as sensors and vision systems may aid in overcoming this reactive state. A vision system could possibly be developed that will allow a robot to identify bacteria in real time and, through a feedback loop, wash areas containing bacteria again or more thoroughly. A robotic cleaning system should contain a range of sensors as well, and a robot could repeatedly take bacteria measurements on key areas. Some bacteria may be beneficial in the sense that they may keep the levels of undesirable bacteria low. Therefore, it is somewhat unclear whether the ultimate goal of cleaning should be a completely sterile environment, and more research is needed to develop a complete understanding of microbiological processes in FPPs.

Several challenges related to the robotic cleaning system have not been addressed in this thesis, including the fact that fish remains are often present after processing in real FPPs. A predefined robotic cleaning path may not remove such matter, and a robot system without a vision system and intelligence will not detect and consider how it could remove such remains in the way a manual cleaner would. The expansion of the robotic cleaning system with vision and algorithms that allow it to detect such remains and learn how to remove them would be a natural extension of the work done in this research project. To ensure that an automatic cleaning system produces satisfactory results, it needs to be able to assess the quality of the cleaning process. For human workers, it is easy to visually determine whether cleaning efforts have produced acceptable results with regard to removing soil and fish residue. However, many different aspects determine whether equipment has been cleaned well enough, such as the presence of blood, fish debris and slime, and bacteria biofilm.

Vision technology has been used for quality control in food applications previously (Dowlati, de la Guardia, Dowlati, & Mohtasebi, 2012). The possibility of detecting blood via a robotic vision system may also improve the impact of a robotic cleaning system from an industrial standpoint, although the absence of blood is not an indicator of a cleaned area. Blood detection has been tested and seems as a promising addition to a cleaning system (E. D. Bjørlykhaug & Egeland, 2019). A complete vision and/or sensory system for detecting fish remains and blood, bacteria, and/or biofilm, together with algorithms for changing and continuously improving cleaning paths based on machine learning, will create a total cleaning solution that could replace manual cleaners and provide comprehensive information concerning cleaning in real time. Some of this technology may be mixed with an Industry 4.0 mindset (Lasi, Fettke, Kemper, Feld, & Hoffmann, 2014) of making large amounts of data available for further analysis and use. It is believed that a robotic cleaning system may be an important step in furthering the knowledge of how bacteria forms and develops in FPPs by enabling documentation of cleaning processes and possibly linking such data to sensory technology. To drive the work of this research field forward, a robotic cleaning system must be implemented at an actual FPP, preferably in parallel with an adjacent processing line and be tested over time to obtain accurate insights concerning how well a robotic cleaning system performs. Such a test would allow several iterations where one could compare manual vs. robotic cleaning effectiveness, and also an iterative refinement of robotic cleaning paths. No experiments in test facilities, whether physical or virtual, will be able to simulate or replicate all of the parameters found in a real-world situation.

To facilitate installation and commissioning of a robotic cleaning system, 3D scanning and 3D simulation (offline programming) are suggested as tools, and advanced sensory and/or vision systems must be developed to realize the full potential of robotic cleaning. Three-dimensional scanning may be used to obtain accurate spatial data to be used for planning and interfaces, and 3D simulation can be used to check for collisions, verify detail designs, and create robotic cleaning paths. The framework proposed by (Eriksson et al., 2018) can be used to formulate requirements in both cases and provide insights as to what outputs are needed for different use cases. By defining the output beforehand, valuable time may be saved when setting up scans and engaging in post-scan work with the data obtained. Errors may also be avoided, and unnecessary reworking may be avoided (e.g. if an area is not captured with enough accuracy for e.g. building solid models). In the future, the framework may be expanded into a broader model of how 3D scanning projects should be approached based on their intended goals and how the features that are important in each of the three classification areas can be further developed. Three-dimensional scanning may be used to bring new customized products to the customer faster, as this technology makes customization easier for developers. More research is needed to develop more automated and faster methods or software with which to convert 3D scans into solid models for this technology to become widely utilized in the industry. Furthermore, new applications and use cases based on the results of 3D scanning beyond the reconstruction phase are needed.

Future work for design for cleaning may include, but may not necessarily be limited to, the development of new materials that are robust enough to withstand harsh environments and have low surface roughness, as well as new production methods, such as 3D printing and robotic welding. Emerging technologies (e.g. surface treatments such as hydrophobic coatings) may also impact design for cleaning in the future. Procedures and/or standards for determining whether a design is hygienic, identifying which properties determine if it is hygienic, and establishing how hygienic it is by some scale, are also lacking; as such, they may also be a future area of research.

6.6 Impacts and Future Perspectives

It is difficult to conclude on the effectiveness of robotic cleaning of fish processing plants based on the one full-scale test presented in this work. However, contours of feasibility are present. The effectiveness of cleaning is vital to ensure satisfactory food safety. This effectiveness may be achievable by introducing robotic cleaning systems, which may be fine-tuned to do the job precisely as instructed each time. Variations in cleaning quality could be a thing of the past. A robotic cleaning system may once fully developed and implemented, replace several cleaners, creating direct savings in labor costs, and reduce costs related to cleaning. The potential revenue saved through fewer callbacks and could be significant, but this potential is hard to anticipate.

Consequently, robotic cleaning may contribute to lower the overall production costs of fish products in the NAI. Critical bottlenecks to solve is the efficient creation and improvement of cleaning paths; how could this be automated and automatically adjusted? These are unanswered questions, but vital to make a robotic cleaning system genuinely competitive. It is conceivable to think that machine learning and artificial intelligence in the future could aid in automatic adjustment of cleaning paths through data collection of cleaning results and equipment layout and design from several processing lines. By further developing the solution with sensory capabilities, a robotic cleaning system may aid in securing a high quality and high food safety of the fish products produced in the NAI. Subsequently, a robotic cleaning system may contribute to increasing the NAI's possibilities of competing against low-cost countries and ensure a prosperous fish industry in Norway. A higher production of finished consumer-products in Norway, in turn, could benefit the environmental impact of fish production through less transport needed from factory to consumer.

A vital realization during the work in this thesis is the interconnectivity between technology and biology to solve the problem of cleaning in fish processing plants. The focus in this work is the technology required to perform cleaning; however, one must achieve a basic level of understanding of how to overcome or battle the bacterial challenges to create meaningful technological solutions. Such an understanding enables the creating of more suitable solutions in respect of the hygienic design of machines as well.

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A. Appendix

A1. The Resulting Prototype 1

A1.1. Mechanical Design

The first prototype consisted of a Universal Robot R10 industrial manipulator mounted on a Rose+Krieger EPX 60 stainless steel linear axis. This axis is oriented to move the UR10 in the vertical direction. The linear axis is suspended below an Igus PR10 rotating slewing ring. This arrangement allows the robot and axis to turn 360 degrees, thus greatly enhancing the working envelope of the robot arrangement. Visualizations in VC showed that it was necessary to expand the workspace of the robot, which was done by providing a movable robot base and a lance mounted at the end-effector. The visualizations showed that a vertical travel length of 2 m and a rotational axis would fulfill the requirement of being able to clean an entire electric stunner.

A1.2. Control System

Both the linear axis and the slewing ring were operated through Omron Sysmac Studio, with the controlling PLC from Omron receiving instructions from the UR10 control system via MODBUS and the UR 10 acting as the master in the control system. The control system is depicted in Figure A.1 and further addressed in Publication 2 (Bjorlykhaug et al., 2017), but it is not further addressed in this thesis.

Figure A.1 Control system of Prototype 1

A2. The Resulting Prototype 2

A2.1. Mechanical Design

The mechanical design of Prototype 2 is shown in Figure A.2 and Figure 5.2 (page 46). It is a 6DOF serial manipulator. Joints 2, 3, 4, and 5 are made of servo motors with their gears being single units; these servo motors act both as bearing elements for the joints supporting both axial and radial forces and movements and handle gear reduction for the motor. The joints are linked together with cylindrical beams with end plates for attaching the joints.

Slewing rings were used for joints 1 and 6 to reduce the overall height in those joints, which results from the combined gearbox and servomotor units used on joints 2–5. Joint 1 is an outward-toothed slewing ring, with ingress to a gear mounted at the tip of a servo motor gearbox. Joint 6 also has a gear mounted at the tip of a servo motor gearbox, but this is connected to a belt, which is in turn connected to a slewing ring. This allows the motor to be offset, which shifts the weight further away from the tool center point of the manipulator. This weight shift allows the geometry to shrink towards the tool center point, which further saves weight and increases the likelihood that the manipulator will be able to access internal areas in need of cleaning.

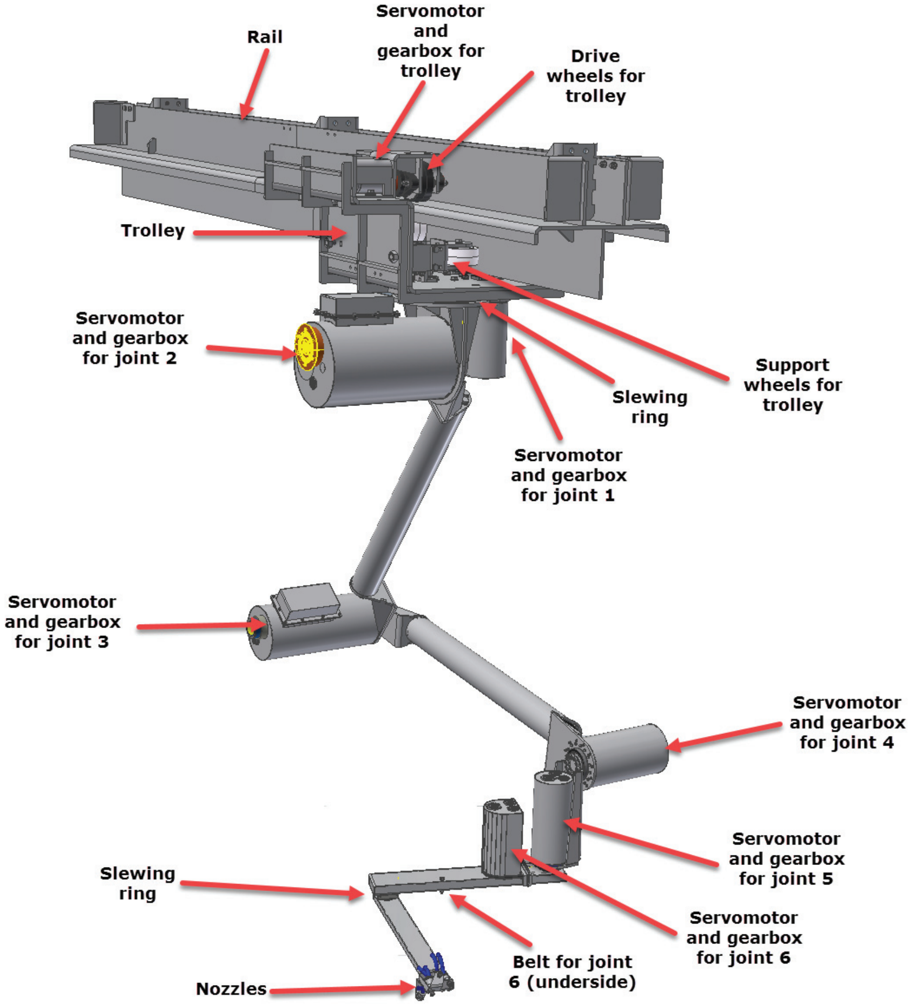

Figure A.2 CAD model of Prototype 2 suspended from the horizontal axis. Servomotors and gears are covered by motor covers to enhance the device's ability to tolerate the environment.

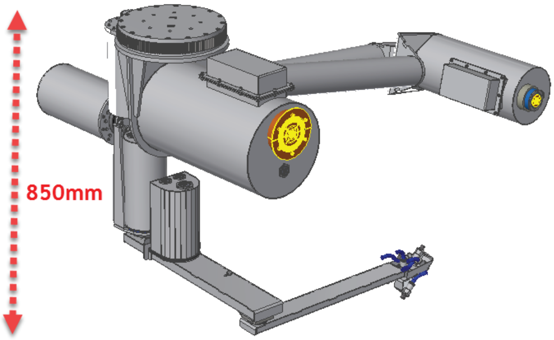

Figure A.3 Fully folded Prototype 2

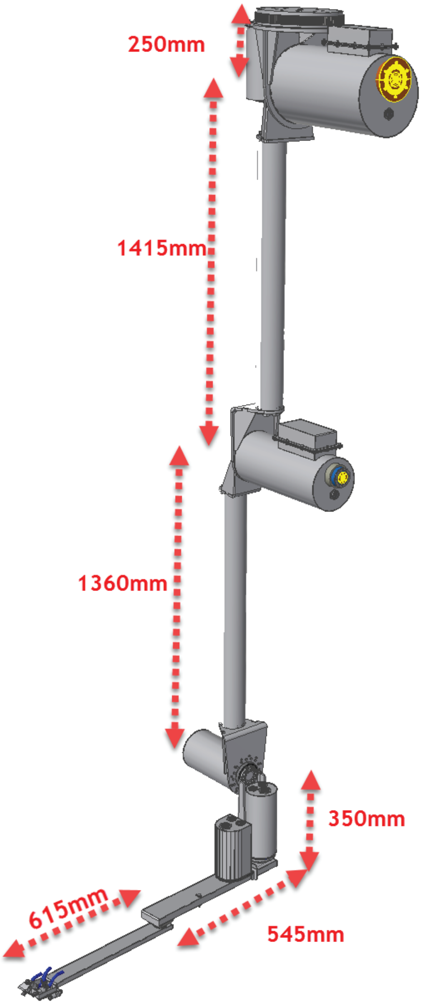

Figure A.4 Fully extended Prototype 2

A2.2. Rail

The rail is made of AISI 304 plates of thicknesses from 8 to 12mm. It is welded together from two sections, each of 1750 mm. As a result of this this design and configuration, the rail can have turns, enabling a greater reach for the robot cleaning system. Manufacturing turns were not needed to achieve the reach required for full-scale testing of Prototype 2. The rail is shown in Figure A.5.

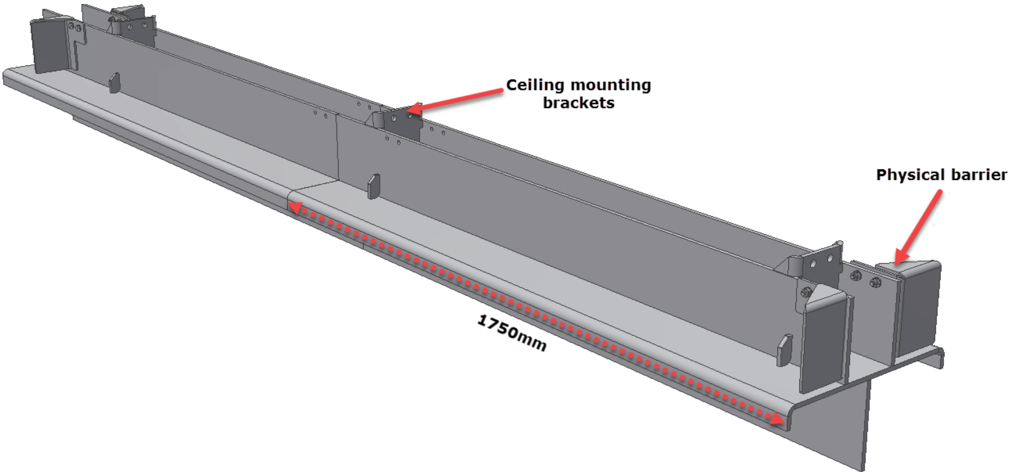

Figure A.5 Custom Rail

A2.3. Trolley

The trolley's main component is a 12-mm AISI 304 plate bent to form a "U with wings," which is depicted in Figure A.6. The trolley is driven by two synchronized servo motors with gears, and it is stabilized by spring-loaded support wheels in both the horizontal and vertical directions. This keeps the trolley centered about the rail and allows it to turn along the rail.

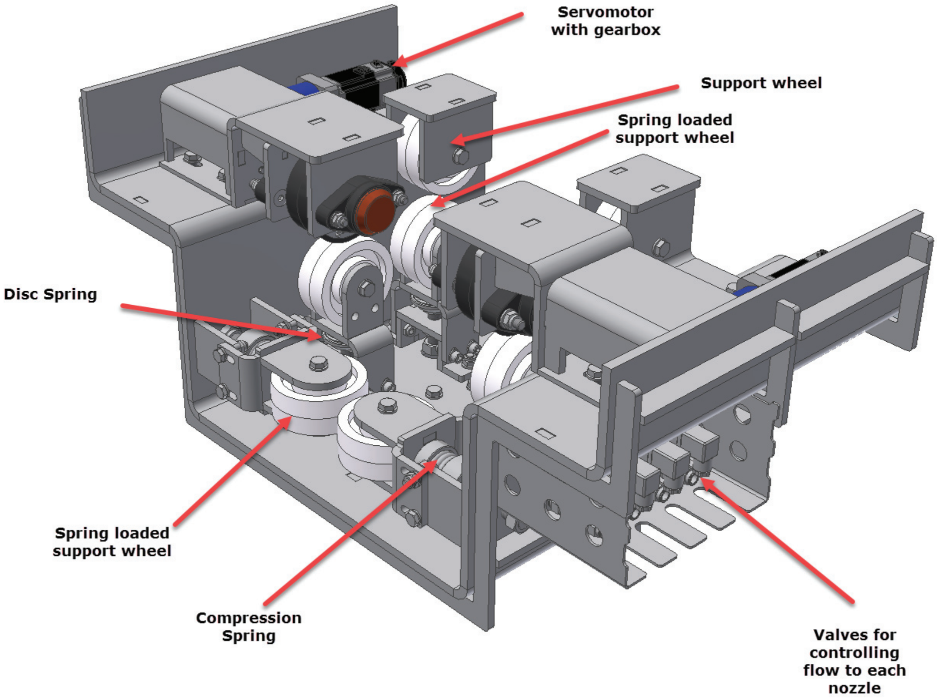

Figure A.6 Trolley for transporting the manipulator along the rail Prototype 2

A3. Detailed Evaluation of Prototypes

Table A.1 Comparison of the prototypes' accommodation of the requirements

Point in time	Requirement	In relation to Prototype 1	In relation to Prototype 2
Initial requirements	· Safety for personnel and equipment in the FPP	Although a UR10 robot has built-in stoppage when meeting resistance and is cleared for work alongside humans, it would be required to equip the solution with additional safety equipment and protocols.	The safety aspect of Prototype 2 was not the main focus during development of the system, although several emergency stop buttons were placed around the test facility, which worked satisfactorily. More automated security, such as physical barriers and/or light barriers/sensors, would be required for an industrialized solution. Torque thresholds for the servo motors should also be implemented. There should also be a system that determines that no cleaners are in the vicinity before cleaning is allowed to start.

Point in time	Requirement	In relation to Prototype 1	In relation to Prototype 2
	· Low cost	Prototype 1 had low costs. The highest costs are those of the linear axis and the robot itself. The total price is seen as acceptable.	The servo motors and drives are expensive; thus, even though the rest of the components used are relatively cheap, there is little difference in price when compared to an industrial robot. The total price is seen as acceptable, however, even when including the rail and trolley.
	· Able to be retrofitted into most existing FPPs	The UR10 is small and nimble enough to fit into most FPPs, but such a solution would require adjusting the length of the vertical linear axis due to height restrictions and the differences among FPPs.	The solution presented as Prototype 2 is fully customizable and may be installed in most existing FPPs.
	· Ensure satisfactory hygiene	The cleaning tests showed good cleaning results; it is believed that they are sufficient for industrial performance.	The cleaning tests showed cleaning results that were on the same level or better than that of manual cleaning.
	· High/long reach of the robotic cleaning system	The main drawback of this prototype is its reach. To achieve a satisfactory industrial performance, the reach and flexibility of the solution must be improved.	The prototype presented has a reach of above 3 m, which is considered sufficient for most FPPs when combined with a linear rail. Were the rail to be expanded with one or more turns, the reach would become exceptionally good.
	· Should replace several cleaning operators	Due to its limited reach, this prototype would probably not replace several cleaning operators and is thus considered insufficient from an economic standpoint.	With its long reach, which may be further expanded either through changing the arm lengths or the length of the rail, Prototype 2 is believed to be able to replace several cleaners. Time was not considered important in the test performed in this project, but the robot should work as fast or faster than manual cleaning operators to fully meet this requirement.
	· Should be able to clean a large portion of an FPP, such as the slaughtering area	Due to its limited reach, this prototype would not be able to clean more than what was cleaned during the experiment without considerable rework with regards to increasing its working area.	The custom robot cleaning system was, in experiment 2, able to clean two central components of a slaughtering line. By increasing the length of the rail, a complete slaughtering line would be possible to clean.

Point in time	Requirement	In relation to Prototype 1	In relation to Prototype 2
	· The robot’s ability to tolerate the environment in which the robot is planned to operate	In order to tolerate the environments found in FPPs, the UR10 is fitted with a raincoat. This raincoat does not protect the robot sufficiently well from water, and it is believed that a UR10 would not last long in an FPP. Also, the rain cover introduces a contamination threat, as splashed contaminated water may travel inside the coat and drip onto cleaned equipment and surfaces. Although the raincoat will offer some initial protection against chemicals, it is likely that some chemicals will damage the aluminum on the UR10 and possibly even the raincoat itself.	AISI 304 and AISI 306 are the main components of Prototype 2, and the servo motors are protected by gaskets made of food grade rubber (white nitrile rubber (NBR)). Standard industry materials are used for hoses, bolts, nuts, and so forth throughout the prototype. All of these materials are resistant to the chemicals used and tolerate the environment well. The system will also tolerate cleaning well as a result of these choices of components and materials.
	· The robot’s ability to tolerate the chemicals which are used during cleaning		
	· Dexterity throughout the working area	The robot showed low dexterity over the working area with the mounted lance. The reach increased, but the nimbleness of the solution suffered due to this.	Prototype 2 as it is may not be flexible and small enough to fully accommodate the needed dexterity, but it has potential to do so through further development. A more advanced nozzle arrangement and a rail system with turns will aid in this regard.
	· Short installation time to reduce impact on production time	The components chosen are mostly of industrial origin and quality, and very little customization is necessary, which enables short installation times.	By capturing 3D spatial data and using this data in the simulation environment, many errors were discovered and fixed before the system was built and tested, and this reduced the installation time required, and should do so in further advancements. This method should be retained as a best practice for further complex installations. The installation time of this robotic cleaning system would probably be longer than for Prototype 1, but by utilizing the benefits of virtual factory layouts and simulations, it is perceived that acceptable installation times are possible.

Point in time	Requirement	In relation to Prototype 1	In relation to Prototype 2
Additional after the first cleaning test	· Low weight	The UR10 has a weight of approximately 30 kg and is well-suited for mounting on ceilings.	When considering the reach of the prototype, the weight of approximately 220 kg is low, and it would be possible to suspend this manipulator from ceilings in FPPs.
	· Small footprint	The robot itself has a very small footprint but requires surrounding infrastructure that may have a large footprint.	The custom manipulator has a small footprint but extending the reach would require a rail system that has a larger footprint and requires surrounding infrastructure.
	· Avoidance of intrinsic contamination - hygienic design – not to impose new contamination threats	The raincoat may cause problems, as bacteria may develop inside it. The main body of the UR10 is made of aluminum, which is undesirable in FPPs due to surface roughness. The rest of the solution is considered "good enough" with regard to hygienic design, although it would probably not withstand the cleaning regimen.	As the robot and rail are custom-built, the knowledge of hygienic design obtained from the industry is implemented was implemented during the development of this solution. It will likely be accepted in the industry as is, but advancements intended to create an even better hygienic design are possible.
	· Sufficient stiffness in the suspension to allow scrubbing or other innovative cleaning methods requiring force on the part of the robot	As the solution is presented the vertical axis hangs freely from the top mount as the solution is presented. When the robot is in its bottom position, the flex of the suspension is considered too high to enable scrubbing; it may even be too high for cleaning should the robot's speed be increased. This could be fixed by, for example, introducing a support between the vertical axis and the ground. However, this would increase the complexity of, and the "disturbance" caused by the installation.	The trolley mounted on the rail and the stiffness in the joints and links of the custom manipulator did not provide sufficient system stiffness to allow, for example, the robot to scrub surfaces, but, given the speed of the manipulator, the stiffness was good enough for cleaning. The weak points are the springs of the trolley and the interface between the trolley and the manipulator. Reworking these points will be necessary to allow for higher speeds.
	· Minimal obstruction to the workspace during normal fish production	The vertical axis introduces a problem by being an obstruction during normal processing, and it is believed that such a solution will not be accepted in its current state.	The rail introduces the possibility of moving the manipulator away from the processing area during normal production, which will be the preferred solution.

Point in time	Requirement	In relation to Prototype 1	In relation to Prototype 2
	· Custom nozzle/nozzle arrangement may be necessary	A 0,5 m lance is mounted on the UR10 to increase the prototype's range, and the standard hose of the industrialized cleaning station is mounted at the end. This does not give satisfactory flexibility in terms of spraying direction.	Prototype 2 has a custom-made nozzle arrangement installed that greatly expands the area in which the robot can spray without changing its position.
Developed during the course of the project	· Few changes of existing processing plant infrastructure	It would require relatively little effort to install the system as it is, but the vertical linear rail is quite obtrusive and would probably cause problems in some FPPs, which would require changes to their layouts.	As the solution may be customized to fit the requirements of each FPP, its installation will likely not require many changes to existing infrastructure. The rail should nonetheless be developed further and be rendered less obstructive to minimize the infrastructure changes required.
	· Short commissioning time to reduce the on-site time required after installation	The UR10 was programmed manually for this test and exhibited limited possibilities in terms of using simulations to shorten commissioning times. A comparable commissioning time would not be accepted in FPPs.	The process of capturing 3D spatial data and using this data to simulate robot cleaning paths worked very well during the cleaning test and will enable short commissioning times at FPPs.
Additional requirements as an outlook after the second cleaning test	· A robotic cleaning system should be easy to use for FPPs (e.g. push a button to start cleaning)	When a UR10 has a finished robot program, the program may be started by the push of a button, without further interaction being required.	The control system for Prototype 2 was convoluted. More work is needed to develop the control system to such a level that a "one-button start" is possible.
	· Reach is more important than stiffness	Both the reach and stiffness of this solution were too low.	The reach was sufficient, but the stiffness was considered slightly too low in this solution, and more work would be needed to stiffen up the system. This would allow the manipulator to achieve greater speeds.

A4. Pictures of different FPPs

Figure A.7 Slaughter line at FPP 3 after cleaning.

Figure A.8 Slaughter line at FPP 3 during production. Notice the blood and fish residue which must be cleaned off after production.

Figure A.9 Slaughter line at FPP 4. Consider the vastly different layout from previous pictures.

Figure A.10 Slaughter line at FPP 5. A different setup in slaughter line.

Figure A.11 Slaughter line at FPP 6. Yet another different slaughter line setup.

Figure A.12 Slaughter line at FPP 7. Notice the much lower ceiling height at this facility compared to other facilities.

B. Appended Papers

Appended Paper 1: Experimental Study of Effectiveness of Robotic Cleaning in Fish Processing Plants

Appended Paper 2: Development and Validation of Robotic Cleaning System for Fish Processing Plants

Appended Paper 3: Improving Cleanability by Innovating Design

Appended Paper 4: Visualization Support for Design of Manufacturing Systems and Prototypes – Lessons Learned from Two Case Studies

Appended Paper 5: Prototyping Installation and Commissioning of a Novel Cleaning Robot Using Virtual Tools – Lessons Learned

Appended Paper 6: Hygienic Standards and Practices in Norwegian Salmon Processing Plants

Appended Paper 2 is not included due to copyright

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Experimental study of effectiveness of robotic cleaning for fish-processing plants

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ABSTRACT

This paper presents the development and experimental testing of the effectiveness of a robotic cleaning system for fish processing plants. The processing of fish introduces a substantial risk of bacterial contamination, which can cause the spoilage of fish and pose a threat to consumers' health. Good operational hygiene and precautions, in addition to regular cleaning of the processing plants, are necessary for the reduction of the risk of contamination. The state-of-the art cleaning techniques currently include manual cleaning operations of fish processing plants. The experiments of robotic cleaning presented in this paper were performed in two rounds. First, a test using a conventional low-cost industrial robot mounted on a vertical linear axis was used. As the results from this test seemed promising, a second robotic system was built aiming at a more industrialized version. This system consisted of a serial manipulator, tailored for the task, mounted on a horizontal transportation system, and a comparison was conducted between the cleaning performed by human operators and that performed by the robotic system. An electrical stunner with a connected conveyor belt, which is a typical installation for salmon processing plants, was experimentally inoculated with a cocktail of fish-spoilage bacteria that were allowed to develop a biofilm. Back-to-back cleaning trials with biofilms of *Pseudomonas fluorescens, Pseudomonas putida, and Photobacterium phosphoreum* confirmed that the industrialized robotic prototype performed equally well or better than the conventional manual cleaning procedure currently used in the industry. The results demonstrate that a robotic system can deliver satisfactory results in the cleaning of fish processing plants, thereby minimizing the potential for the spread of contamination. The proposed robotic concept allows for an automated cleaning system, reduced human labor, increased profitability for the industry, and better stability of the cleaning process.

1. Introduction

In this paper, the results from a research project in the Norwegian aquaculture industry are presented. The aim of the project is to develop a robotic system for cleaning fish processing plants, whose performance is equal to or better than that of the manual cleaning procedure that is currently followed.

The Norwegian aquaculture industry has a yearly revenue of over EUR 6 billion for salmon alone (Statistics Norway, 2018). Owing to the fact that there will be an increasing need for protein food sources to accommodate the anticipated growth in population toward 2030 (FAO Food and Agriculture Organization of the United Nations, 2016; World Bank, 2013), the salmon aquaculture industry is expected to grow as it is an important protein food source. However, the salmon industry faces critical challenges that may limit its further growth. One of these challenges is the contamination by the human pathogenic bacterium *Listeria monocytogenes* during production; as of yet, the pathogen has not been fully controlled in food production (Buchanan, Gorris, Hayman, Jackson, & Whiting, 2017). This has led to strict requirements from the Norwegian Food Safety Authority (Mattilsynet - The Norwegian Food Safety Authority, 2016), which is the governing body for safe food production in Norway. Additionally, there is an increasing demand for fresh, chilled fish. Microbiological control of spoilage bacteria, such as *Pseudomonas* and *Shewanella*, determines the quality

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and shelf life of fresh fish (Gram & Huss, 1996; Møretrø, Moen, Heir, Hansen, & Langsrud, 2016). In view of these challenges and the anticipated growth of aquaculture, there is a need for the industry to find new ways to improve its procedures in all stages of the value chain, from breeding to slaughtering and processing, including the improvement of the cleaning procedures, to reduce the risk of bacterial contamination that may pose a potential risk to human health.

Efforts have been made by researchers and companies to automate and rationalize the different production processes, such as the use of robots and automated systems in different gripping and handling tasks, slaughtering operations, as well as de-heading and filleting (Aadland, 2018; Asche, Cojocaru, & Roth, 2018; Buljo & Gjerstad, 2013; Mikkelsen, 2017; Paluchowski, Misimi, Grimsmo, & Randeberg, 2016; Sandvold & Tveterås, 2014; Sund, 2016). Efforts of implementing machine learning in fish processes, such as segmentation of fish and species identification (Hassanien, Tolba, Elhoseny, & Mostafa, 2018) are also a part of the exertions to automate more of the fish processing industry. Despite this, the total amount of industrial robots in the food industry reached 9700 units in 20017, less than 3% of the total supply (International Federation of Robotics, 2018), and most are used for packaging/palletizing operations. The contemporary salmon industry has access to advanced equipment and systems for all stages within its value chain; however, the processing speed is negatively affected by several manual interventions, such as cleaning, that continue to be necessary (Asche et al., 2018). Furthermore, regarding the value chain of the fish, the automation of the open cleaning process has not yet been investigated; nevertheless, efforts have been made in other cleaning aspects, such as the cleaning of tanks that are used in aquaculture (Mcrobbie & Shinn, 2011). Systems for Cleaning-In-Place (CIP-systems) are common and well developed to clean pipes and other closed systems (Cramer, 2013). Cleaning is the last process step during daily fish processing.

To cope with the risk of bacterial contamination, processing plants must be thoroughly and frequently cleaned (Christi, 2014; Windsor & Tatterson, 2001); more specifically, salmon processing plants need to be cleaned daily. Cleaning is performed by cleaning crews after the production has stopped; for several processing plants, this take place during the night owing to double processing shifts. The cleaning costs up to EUR 1 million in labor per year for a processing plant owing to high wages (including bonuses related to the poor working conditions and working during the night). In addition, there are high expenses related to chemicals and water. Moreover, the chemicals produce a spray cloud inside the processing plants during cleaning, which pose health hazards to the cleaning personnel. A typical “spray mist” can be seen in Fig. 1. Furthermore, manual cleaning causes significant strain to the body from repetitive movements. The hoses that are used are heavy, and owing to high-pressure water, they are difficult to handle. Cleaners may also be required to climb on equipment to reach inaccessible areas. Overall, manual cleaning of fish processing plants requires considerable heavy lifting. A robotic cleaning system could reduce the overall cost by reducing the cost of labor and by potentially reducing the amount of chemicals and water used during cleaning. In addition, it could improve the health, safety and environment (HSE) compliance for the workers by reducing their exposure to the hazardous cleaning environment. Furthermore, a robotic solution could stabilize the cleaning process as it would perform the task in the same manner each time, thus removing the “human element,” where different cleaners may perform the tasks in a different manner. Finally, it is likely that a robotic cleaning system would perform the task faster than manual cleaners. Robot technology in general, not just for cleaning, is foreseen to play an important role in intelligent food manufacturing, replacing manual work operations in several steps along the food processing chain (Khan, Khalid, & Iqbal, 2018). As mentioned, robotic technology is implemented on some operations in the salmon industry, however, cleaning of salmon processing plants are still subject to time consuming and costly manual labor (Løvdal, Giske, Bjørlykhaug, Eri, & Mork, 2017) and problems with bacteria do occur.

Fig. 1. The environment in which a robotic cleaning system will operate.

Buzby and Roberts (2009) estimated that the worldwide cost of all foodborne diseases was $1.4 trillion per year. *L. monocytogenes* is, next to *Salmonella*, by far the most frequently reported pathogenic microorganism in the Rapid Alert System for Food and Feed; notifications owing to this pathogen have increased in the EU since 2009 (European Commission, 2015). The product categories that dominated the *L. monocytogenes* notification reports were fish and fish products, often leading to trade embargoes of these products (EFSA, 2013; Nielsen et al., 2017). Recalls, consumer complaints, and bad public relations due to *L. Monocytogenes* contamination in commercial food products significantly contributed to economic losses in the food industry. An illustrating example is the 2008 Canadian listeriosis outbreak linked to cold cuts from a Maple Leaf Foods (MLF) plant in Toronto, Canada. Although MLF instituted a voluntary recall before the outbreak was linked to their plant, the outbreak cost the company in excess of $50 million including market losses, as well as lawsuits and compensations for victims and their relatives (Greenberg & Elliott, 2009). Since 1999, the EU, Norway, Switzerland, Canada, Australia, and New Zealand have all introduced a quantitative legal limit of 100 *L. monocytogenes* colony forming units (cfu) per gram, which is applied for a wide range of food products, including the most susceptible ready-to-eat (RTE) products where *L. monocytogenes* is able to proliferate, such as cold-smoked salmon products (Løvdal, 2015). USA has an even stricter legislation (i.e. zero-tolerance) for RTE products resulting in an extremely high rate of recalls from the market for potential listeriosis hazard (Goetz, 2013). Thus, measures to reduce the risk of bacterial contamination in general, particularly contamination due to *L. monocytogenes*, are imperatively necessary and sought after by the salmon industry. To safeguard food safety, it is crucial that the proposed robotic systems can perform equally well and, preferably, better than the present manual cleaning practices. The objective of the present study is to first develop and optimize, and then to evaluate the performance of a robot prototype in comparison with a contemporary manual cleaning practice in a controlled set-up using inoculation with relevant salmon spoilage bacteria that formed artificial biofilms.

1.1. Future perspective

Robotic cleaning systems have already been well established in the literature. However, most robotic cleaning systems were focused on the cleaning of flat surfaces, e.g., floors (Palleja, Tresanchez, Teixido, & Palacin, 2010), walls (Lee et al., 2018), windows (Houxiang Zhang, Jianwei Zhang, & Guanghua Zong, 2004), and solar panels (Jaradat et al., 2015). Cleaning systems may be able to operate in large areas;

nevertheless, they are limited to moving in two dimensions, and they typically do not operate in 3D space. However, there are exceptions. Cleaning systems, such as hull cleaning (Ortiz et al., 2007) and car/truck washers (Yu, Kurnianggoro, & Jo, 2015), can operate in three dimensions and can clean objects of arbitrary shape. However, to the knowledge of the present authors, there are no research works in the literature focused on robotic cleaning for fish processing plants. Conventional robotic manipulator designs do not fulfill the requirements of a robotic cleaning system for fish processing plants (Bjørlykhaug, Giske, Løvdal, Mork, & Egeland, 2017). Several aspects of the robotic design deserve extra attention for a robotic cleaning system focused on fish processing plants. Special consideration regarding the corrosion resistance, the intrinsic contamination, and the transportation system, among others, must be considered to deliver a satisfying operating performance. In addition, a robotic manipulator suitable for cleaning fish processing plants should have a long reach (> 2 m); however, it would have a lower payload requirement than typical industrial robotic manipulators. The robotic manipulator itself must have long reach, be slender, have good dexterity, and provide adequate payload; meanwhile, its weight should be as low as possible. Moreover, the footprint should be kept as low as possible, and the system itself should be unintrusive because modern salmon processing plants often have limited space available for such installations. Moreover, a robotic cleaning solution should impose minimal contamination threats, thus adhering to hygienic design guidelines (EHEDG Secretariat, 2004; Giske, Mork, & Bjoerlykhaug, 2017), to facilitate its efficient cleaning.

There is no existing literature that documents the effectiveness of robotic cleaning for fish processing plants. Our novel contribution documents that such a system can deliver satisfactory results, enabling this technology to be implemented in the industry. This work is an extension of the work conducted in Bjørlykhaug et al. (2017).

The remainder of the paper is organized as follows: First, the two robot systems are presented in Section 2. The setups of the experiments are presented in Section 3. In Section 4, the results from the two different experiments are presented. Finally, in Section 5, the present work is concluded, and further work is discussed.

2. Robotic system

Here, we will present the robotic system used in the experiments. The experiments were conducted in two separate occasions, with two different robotic systems. The systems were designed according to the challenges related to installing such a system in a real-world processing plant. Examples of the equipment layout inside a plant are shown in Fig. 2; Fig. 3 depicts typical installation locations for a future robotic cleaning system.

Fig. 2. Slaughtering line at facility 1.

Fig. 3. Slaughtering line at facility 2.

2.1. System 1

The first robotic system consisted of a conventional serial robot, namely the UR10, mounted onto a vertical linear axis with a slewing ring, as shown in Fig. 4. In addition, a 1 m long lance holding the nozzle was mounted on the end effector. The combination of these factors enabled the robot, which originally had a reach of 1300 mm, to cover a complete electric stunner. This system was manually programmed “online”, jogging the robot from point to point and creating a cleaning path. An overview of the architecture can be seen in Bjørlykhaug et al. (2017).

2.1.1. Cleaning system

The cleaning system was composed of the industrial cleaning station

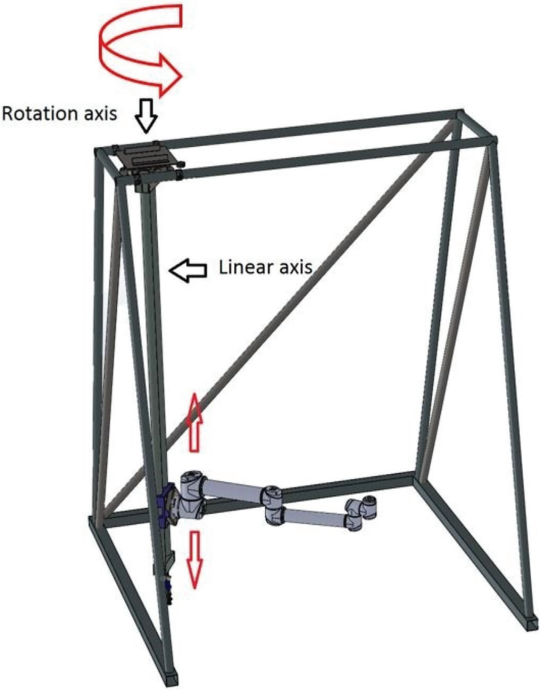

Fig. 4. A CAD model of the linear axis and the rotational axis assembly. A support frame was manufactured to suspend the assembly from the ceiling.

Fig. 5. A CAD model of robot 2, mounted on the horizontal linear axis.

4 K on wheels by System Cleaners. This equipment required 400 V AC and its input was regular pressure water. The output was high-pressure water or a mixture of air, chemicals, and water, used for spraying foam. The end could hold different types of nozzles based on which mixture is sprayed. The end of the accompanying hose was attached to the UR10 robot in Experiment 1 and it was used directly.

2.2. System 2

This system was an upgrade of System 1 and it was an effort to eliminate the drawbacks of System 1. Instead of a conventional robotic manipulator from a commercial supplier, a custom robotic manipulator tailored to the task was constructed, as can be seen in Fig. 5.

In addition, the robot was mounted on a custom horizontal linear axis suitable for installation in the harsh environment of fish processing plants, with the necessary hygienic considerations. The robot itself is a long-reach, slender robot, with a low payload capability (compared with typical industrial robots of the same reach), thereby maintaining the manipulator weight as low as possible. The robot and its kinematic chain are shown in Fig. 6 and Fig. 7, respectively. At full horizontal extension, the robot has a reach of 4 m; furthermore, its weight was approximately 220 kg.

2.2.1. Cleaning system

The cleaning system of Experiment 2 was identical to the one in Experiment 1, except for the fact that the hose was separated into six different hoses, each of which had their own solenoid valve that could be controlled to be switched on or off. Each of the six hoses continued up to the end-effector of the robot, where six identical nozzles were mounted at an angle with respect to each other, as seen in Fig. 8. For different parts of the cleaning procedure, a different number of nozzles was used. This eliminated the need for extra degrees of freedom (DOFs) close to the end-effector of the robot, thus removing the need for a servomotor near the end effector; this minimized the weight and made the robot slenderer.

Fig. 6. Robotic system 2 in the test facility.

2.2.2. Control system

One of the main limitations of System 1 was the manual programming of the robotic system. This proved to be excessively time consuming and tedious; therefore, a better approach was required, particularly considering that a potential industrialized version would be installed in different plants, thus requiring different paths to be programmed. Offline programming of the robot movements was decided to be the preferred approach. Because the robot was built anew, a control system had to be developed. For the control system, a distributed approach was used. Instead of implementing the kinematics of the robot in the programmable logic controllers (PLC), which controls the servos, a computer program calculated the actuator positions for the desired robot pose. A schematic detailing the control system approach is shown in Fig. 9. For a more thorough explanation of the trajectory generator, we refer to Bjørlykhaug (2018).

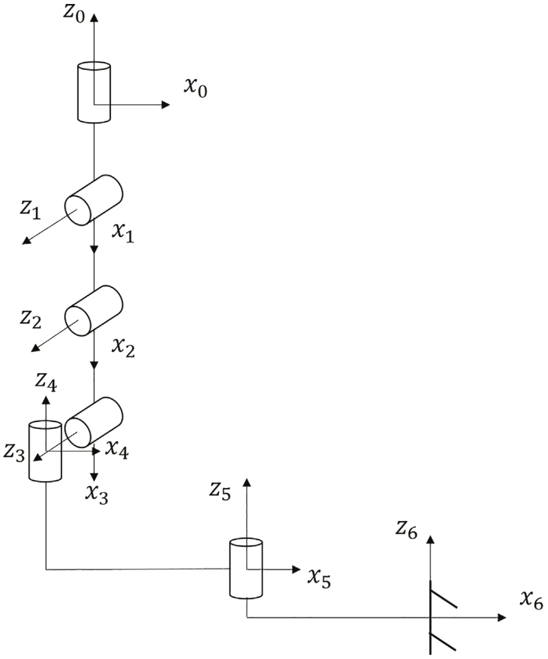

Fig. 7. Kinematic chain of the custom robot in prototype 2.

2.2.3. Horizontal transportation system

The manipulator was mounted onto a horizontal linear axis to expand the work envelope of the robotic system. Similar to the manipulator, the linear axis was also built specifically for the task. Fish processing plants often have a processing layout that is not in a straight line. Unlike conventional linear axes, which are limited to a straight line of motion, this one has a modular design that was built from sheet metal building blocks, thus enabling curvature. With curvature, the axis was able to navigate the robot base in 2D, which potentially covered the complete processing plant depending on the particular plant layout.

3. Method and tools

Here, we will present how the experiments were set up for both cases. A physical experiment to measure the cleaning effect of robotic cleaning was the chosen method for both systems.

3.1. Experimental setups

3.1.1. Experiment 1

Regarding the methodology for Experiment 1, we refer to Bjørlykhaug et al. (2017). The robot in action during Experiment 1 is shown in Fig. 10.

3.1.2. Experiment 2

Experiment 2 was set up as back-to-back experiments between cleaning by human operators and cleaning by the robotic system. The equipment used to perform the cleaning test consisted of an electric stunner and a conveyor used for gill cutting, both of which can be typically found in fish processing plants. These machines are often considered among the most important machines for cleaning, as they are situated immediately after the fish has been pumped into the processing facility. Typically, the machines are filled with fish residue, fish protein, fish slime, and fish parts (of fins). Because this is where the gills are cut, blood is usually spilled on a large part of these machines. The

Fig. 8. Nozzle arrangement.

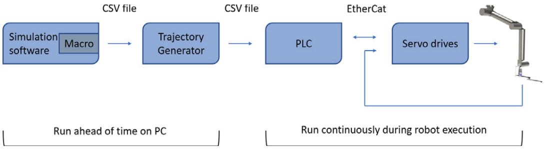

Fig. 9. Overview of the control system.

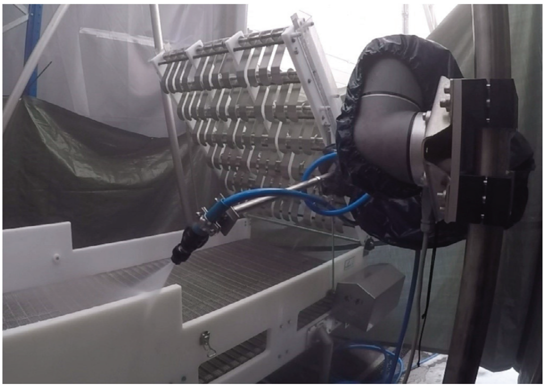

Fig. 10. Prototype 1 during experiment 1.

Fig. 11. Spraying of the inoculation mixture in Experiment 2.

dimensions of the mini fish slaughtering line cleaned in Experiment 2, as well as the sampling points for microbiological analysis are shown in Fig. 12. A length of almost 6 m and a width of a little over 1 m is close to a typical installation at a fish processing facility.

3.1.3. Microbiology analysis

The electric stunner and conveyor were inoculated, as seen in Fig. 11, with a bacterial suspension cocktail of *Pseudomonas fluorescens* MF05002 (Møretrø et al., 2016), *Pseudomonas putida* ATCC 49128 from the American Type Culture Collection, and *Photobacterium phosphoreum* CCUG 16288 from the Culture Collection University of Gothenburg. Bacteria cultivation, inoculation, and sampling were performed as previously described (Bjørlykhaug et al., 2017), with only minor modifications. All bacteria were initially grown separately to a stationary phase at 30 °C and 150 rpm in a shaking incubator in a tryptic soy broth with 0.6% of yeast extract (TSBYE; Oxoid). Bacteria were pooled together at 250 mL of each strain in 1 L of sterile polyethylene bottles, which were then topped up with 250 mL of fresh TSBYE. The bacteria were maintained at ambient temperature (10–20 °C) and were used within 72 h. The inoculation was performed by spraying the bacteria using a household spray flask on all open surfaces. Spraying was repeated once each hour four times. Twenty-four hours after the first spraying, an incomplete biofilm had developed on the surfaces (approximately 10^6 cells·cm^{-2}). Prior to washing, eight predefined control points were sampled using Sodibox cloths (Sodibox, La Fort-Fouesnant, France). After the manual washing procedure had been completed and the stunning machine had been air dried, an additional eight predefined control points were sampled using Sodibox cloths (Fig. 12).

The following day, the same routine was repeated for the robotic cleaning using bacterial suspensions of the same age as for the manual cleaning. The samples were maintained at 4 °C and were plated 48 h after sampling. Sodibox cloths were suspended in 100 mL buffered peptone water (Oxoid) and were subject to homogenization using a stomacher machine (Seward) for 2 min. Serial dilutions of the samples were spread-plated in triplicate on tryptic soy agar with 0.6% of yeast extract (TSAYE; Oxoid); then, they were incubated at 30 °C for 48 h before the bacterial concentrations were calculated as cfu per cm^2. The data are presented as logarithmic reductions in the plate counts (ΔN) between the counts before (N_0) and after (N_x) cleaning, namely $\Delta N = \log N_x - \log N_0$.

3.2. Cleaning procedures

A general cleaning process for fish processing plants is formulated in (Mariott & Gravani, 2006):

1. Cover electrical equipment.
2. Remove large debris.
3. Remove soil deposits from the equipment, walls, and floors, proceeding from top to bottom towards the drains.
4. Disassemble equipment as required.
5. Pre-rinse the equipment with water at 40 °C or less.
6. Apply a cleaning compound effective against organic soil (typically an alkaline cleaner), with a temperature lower than 55 °C.
7. Wait for approximately 15 min to allow the cleaning compound to work.
8. Rinse the equipment with water at 55–60 °C.
9. Inspect equipment and the facility for effective cleaning.
10. Apply a sanitizer, typically a chlorine compound

This procedure coincides with the cleaning procedures typical in Norwegian fish processing plants (Løvdal et al., 2017).

For our case, Steps 1, 2, 3, and 4 would not be necessary to be followed in any of the experiments owing to the non-existence of fish debris and the absence of electrical equipment. The test equipment was designed in such a way that the disassembly would not be required prior to cleaning as part of the daily cleaning routine.

For the cleaning process in Experiment 1, please refer to Bjørlykhaug et al. (2017). The cleaning process in Experiment 2 was performed as follows: the equipment was hosed down using cold high-pressure water at first. Immediately after hosing down all machines, a thick foam of *Lilleborg Enduro Super* with a diluted pH of 12,5 was sprayed on. This was allowed to stay on for 10 min before being washed off by using cold high-pressure water. Then, a foam layer of *Lilleborg*

Fig. 12. Control points and dimensions of equipment in Experiment 2. The electric stunner in the cleaning position with the conveyor belt connected at the front. Sampling points for microbiological analysis in Experiment 2 are indicated as follows: S1 and S2 are steel lamellae on the electrical stunner; P1 and P2 are plastic walls inside the electrical stunner; S3 and S4 are steel cross-beams under the belt of the conveyor and the stunner, respectively. P3 and P4 are the inside plastic walls on the conveyor and the stunner, respectively. (Care was taken not to sample the same areas before and after cleaning).

Fig. 13. Manual cleaning in Experiment 2.

Titan 951, a disinfectant of pH 7 (diluted), was sprayed on and was allowed to stay on for 10 min. Again, the equipment was washed down with cold high-pressure water. This procedure was performed first manually by one cleaner, as seen in Fig. 13; after the equipment was inoculated with bacteria again, the robot system repeated the same cleaning procedure. The cleaner performing the manual cleaning was employed at an undisclosed fish processing plant as the team leader for all cleaners with 15 years of experience in cleaning fish processing plants. He performed the cleaning as he would have normally done.

The robot was programmed offline in the simulation software, as shown in Fig. 14. The prototype in the test facility is shown in Fig. 6.

Our cleaning procedure differs slightly from the general procedure detailed above. We followed the general recommendations of the professional cleaner who performed the manual cleaning, which is the industry standard. Moreover, we did not have access to hot water at our test facility. However, it is common practice in the industry to use cold water.

4. Results

We present the results from both experiments. The robot in Experiment 2 can be seen spraying water and soap in Fig. 15 and Fig. 17, respectively. In this study, the cleaning times for manual and robotic cleaning were not of primary importance; however, they are listed in Table 1 for comparison.

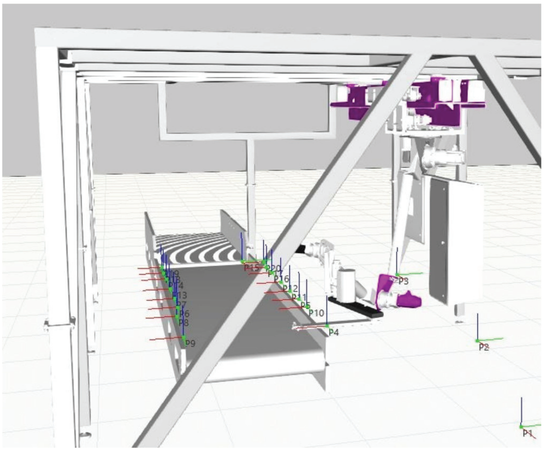

Fig. 14. Simulation of the cleaning process.

Fig. 15. Prototype 2 spraying water.

4.1. *Microbiology*

The decrease in the bacteria count in Experiments 1 and 2 can be seen in Fig. 16. The decrease in bacteria after robotic cleaning in Experiment 1 (Fig. 16A) was promising, and the bacteria count was between 10 and 100 cfu cm^{-2} for all control points, compared with 10^3 to 10^5 cfu cm^{-2} prior to cleaning.

In Experiment 2, the decrease in microbial count for both manual cleaning and robotic cleaning was substantial, as seen in Fig. 16B. In this trial, the inoculated bacterial load was higher than that in Experiment 1, *i.e.*, between 10^5 and 10^7 cfu cm^{-2}. This difference is presumably attributed to the significantly higher temperatures (~20 °C) of growth compared with the ones in Experiment 1 (~5 °C), combined with a slightly extended time between the inoculation and the cleaning. In Experiment 2, the bacterial load after both manual and robotic cleaning was between 1 and 200 cfu cm^{-2}. Although the data were too sparse for us to perform a statistical comparative analysis, it is clear that the robot performed the cleaning at least as well as or better than the operator in this particular case (Fig. 16B).

Table 1

Comparison of the manual and robotic cleaning time in minutes.

Cleaning procedure	Rinsing	Foam soap	Rinsing	Foam disinfectant	Rinsing	Total time
Manual time	6	2	10	1,5	5,5	45[a]
Robotic time	33	33	33	33	33	185[a]

[a] Included in the total time is 2 × 10 min of waiting time between applying foam and rinsing to allow the chemicals to work.

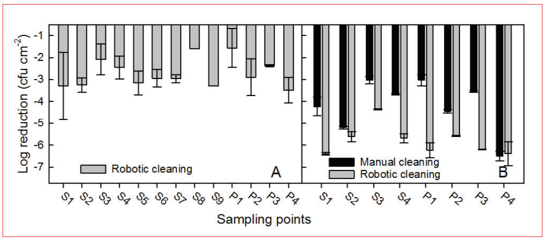

Fig. 16. Bacterial log reduction as an effect of robotic cleaning in Experiment 1 (A) and as an effect of manual and robotic cleaning in Experiment 2 (B). S = Steel and P = Plastic. For sampling points in (B), see Fig. 12. Data in (A) are redrawn from Bjørlykhaug et al. (2017). Error bars represents standard deviation (SD) of n = 3 triplicate plates per sample with error in log Nx and log N0 propagated ((SD log Nx2 + SD log N02)^{½}).

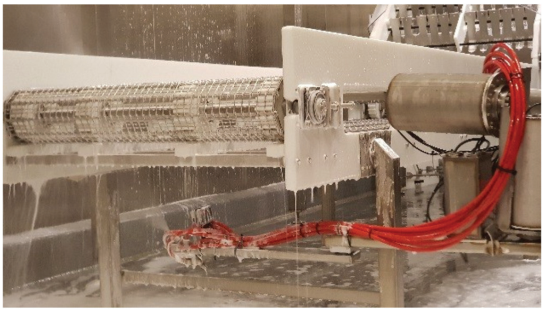

Fig. 17. Prototype 2 spraying soap.

5. Discussion

A main limitation of this work is that only one instance of both experiments was performed. Performing additional repetitions of the same experiments would result in a more reliable measurement of the effectiveness. Additionally, these experiments were performed in a closed scenario. Testing in a real-world processing plant might have affected the results in a certain manner. However, Experiment 2 was performed at a technology readiness level (TRL) of 5–6 (Horizon 2020 Work Programme Commission, 2014), and clearly illustrated the validity of robotic cleaning. The sprayed bacteria produced a biofilm that is close to the real biofilm often found in fish processing facilities; the experiments showed that the robot was fully capable of washing the biofilm away, thus inhibiting the establishment of niches known to facilitate growth of spoilage bacteria and human pathogenic bacteria, such as the. *L. monocytogenes* (Møretrø & Langsrud, 2004).

An even more industrialized version of the robot is required in the future and tests in a real-world fish processing plant is the only manner to validate if the robot can perform as well or better than a manual cleaner. Furthermore, it would be beneficial to combine the robot solution with a vision system to detect blood or microorganisms; these would eliminate the need for manual control after cleaning.

It is probable that the optimization of the robot program related to information collected from several trials, both in the laboratory and in real life, in a fish-processing factory will further improve the cleaning results, particularly in corners and places of limited accessibility.

Corners and spaces of limited robot accessibility can be evaluated for a redesign, layout altering, or a more hygienic design as well (Giske et al., 2017). Robot cleaning can be considered as a method to standardize the cleaning process compared with human operators, as the robot will perform the task equally well on each instance. The standardization of the cleaning process will also stabilize the method, which is one of the core principles in lean manufacturing (Liker & Meier, 2005), thus enabling a more predictable performance of the cleaning process, which can be used in further efforts to further stabilize the fish processing in general. This will allow for incremental improvements from several aspects; the robot operation itself, the design of the equipment, and even the type of materials (stainless steel, plastic, etc.) can be adapted for optimal cleaning processes. In addition, high-temperature steam or new chemicals that may not be allowed or are suitable to be currently used owing to the HSE requirements or considerations, may now be possible to be used.

Furthermore, the robotic system can store the cleaning operation in an electronic format and offer it as proof of the cleaning quality to the customers, thus substantiating that their fish products are produced in an environment that does not compromise quality. Fish processing companies claim that this is key in competing in the global seafood market.

The robot performed the cleaning at a relatively slow, steady pace during Experiment 2. The speed was limited owing to vibrations in the system, which became great if the speed was increased. In this research, only the cleaning results were the focus, and not the cleaning speed. In the next version, the robot design will be upgraded so that the robot may achieve higher speeds and accelerations; and it is still believed that a robotic solution will perform the cleaning tasks faster than manual cleaning operations. Furthermore, it is also possible to use several robots to clean different areas. When cleaning a large area, the waiting time may be neglected because the robot can rinse the first part of the area immediately after the application of the chemicals on the last part of the area.

In addition, robotic cleaning of fish processing plants may reduce cleaning costs. A manual cleaner in Norway earns EUR 60-70 k per year; the suggested solution could easily replace several cleaners. In a robotic cleaning concept, one could possibly even allow increased cleaning time as the main cost, whereas manual work hours would be reduced. Even further savings are predicted when tuning the robot to use exactly the amount of water and chemicals that are needed for the task, instead of consuming random amounts used in modern manual cleaning processes.

6. Conclusion and future work

It can be concluded that although the robot system has its limitations in its current form, a robotic cleaning system can perform the cleaning as well as or better than manual cleaning. Additionally, the repeatability of a robotic system compared with human operators will potentially ensure better hygiene and control of bacteria that develop in fish processing plants over time.

6.1. Future work

Future work related to robotic cleaning will need to focus on installing a robotic cleaning system in a producing fish processing plant. This will enable long-term measurements of the effectiveness of robotic cleaning at a higher TRL. There are still certain challenges that have not been addressed by the experiments conducted in this study, including the fact that in real-life processing plants, certain fish remains are likely to be present on the equipment. This is because the robot only performs a predefined cleaning path and does not consider how to identify and hose away the remains as a manual cleaner would do. The robotic cleaning system must be expanded into including vision and algorithms for the detection of fish remains, as well as be taught how to hose away such residue for it to fully replace manual cleaners. The possibility to develop a vision system to detect blood and biofilm should be investigated, as well as its use for the programming of the robot, and possibly for measuring cleaning results. Machine learning and simulation could also be used to enable the robot to program itself, and to use cleaning results to optimize the cleaning path.

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Review paper
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IMPROVING CLEANABILITY BY INNOVATING DESIGN

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Abstract

Providing safe-to-eat consumer fish products is a key objective for the Global Aquaculture Industry. Cleaning of the process equipment is crucial to meet the demands for fish quality, but also environmental issues and human safety must be taken into consideration. Design of Easy-to-clean fish processing machineries is an efficient and innovative perspective which could be a game changer in the Aquaculture Industry.

Based on the generic hygienic design principles stated by EHEDG and experience collected in a in a research project in the Norwegian Aquaculture Industry, this paper presents four specific design concepts for state of the art fish processing machineries, which is an attempt to interpret EHEDG guidelines to actionable design changes suiting the Norwegian Aquaculture Industry and the type of Original Equipment Manufacturers serving this industry. The development of the design concepts is done by extensive prototyping work, and continuous testing and evaluation in real industrial environment, and there have been numerous iterations in the development of the design concepts. The design concepts have been implemented into several industrial applications for fish processing machineries, and have been under operation at fish processing factories for more than 6 months.

The Hygienic design concepts implemented on fish processing is expected to reduce the risk for *Listeria monocytogenes* and other bacterial contamination in the fish processing factories, reduce the demanding cleaning work in the fish processing factories, reduce usage of chemicals and water in the cleaning process. The experience collected after over 6 months support the expectations. The paper also elaborates future research work in the area of hygienic design principles and concepts.

***Key words**: Design, Design for Cleaning, Cleaning, Innovation, Fish processing.*

1. Introduction

Equipment and machines in the aquaculture industry must be designed to facilitate easy cleaning and disinfection and ensure food safety [1], and thus this is also a requirement from fish processing plants to Original Equipment Manufacturers (OEM's). This paper will follow the design innovations to improve the ease of cleaning the equipment done by an OEM in the Norwegian aquaculture industry. The design studied is related to one specific product group, namely conveyors.

The Norwegian aquaculture industry is big, with domestic sales of salmon and trout around 46 bill. NOK (4.45 bill. EUR, or 5.24 bill. USD) in 2015 in Norway, and with exports of almost 50 bill NOK (5.01 bill. EUR 5.9 bill USD) in 2015 [2]. The industry is making a lot of money since the price per kilogram of fish is high. There are several factors that could be improved to further increase the earnings, one of which is to cut the costs of cleaning.

1.1 *Listeria* spp.

Fail-safe procedures for the production of *Listeria*-free products have not been developed. The most critical areas for the prevention of contamination are: plant design and functional layout, equipment design, process control operational practices, sanitation practices, and verification of *Listeria monocytogenes* control.

L. monocytogenes can adhere to food contact surfaces by producing attachment fibrils, with subsequent formation of a biofilm, which impedes removal during cleaning. The attachment of *L. monocytogenes* to solid surfaces involves two phases: 1. Primary attraction of the cells to the surface and; 2. Firm attachment following an incubation period.

Various studies have demonstrated that *L. monocytogenes* is resistant to the effects of sanitizers, like the effects of tri-sodium phosphate (TSP), especially after a colony has grown on the surface and biofilm has formed. It is more resistant to cooking processes than other pathogens. *L. monocytogenes* is susceptible to irradiation. Generally, the extrinsic factors that have the greatest effect on microbial growth kinetics are: temperature, oxygen availability and relative humidity [3]. *Listeria* spp. is found "everywhere", or in: earth, water, vegetation and raw fish, but in small quantities, so it is expected that some listeria will find its way into fish processing facilities [4], however the important point is to clean it away after the processing is finished to keep it from forming biofilms and growing.

It is clear then that equipment which is poorly designed with regards to cleaning could be a source of contamination which could lead to, in the most extreme case, death. Another aspect of equipment which is poorly designed for easy cleaning is the considerable additional expenses for processing plants [5]. When the equipment is poorly designed, it is more difficult to clean, which exposes the equipment for more wear and tear due to harder use of chemicals, which eventually could degrade the lifetime for the equipment. In addition, it is a hazard for contamination, and it could be necessary to replace the equipment.

1.2 Cleaning

When producing salmon and/or trout, the factory has to be cleaned every day in order to avoid growth of bacteria, especially the previously mentioned *L. monocytogenes*, which is the most unwanted bacteria [6], and the main concern. It causes 2,500 serious illnesses and 500 deaths annually in USA, it can survive 0 - 45 centigrade and it grows well in damp environment. *Listeria* also thrives in neutral to alkaline pH but not in highly acidic environments. The growth rate in pH from 5 to 9.6 depends on substrate and temperature. Human listeriosis may occur in humans if they eat meat with listeria, with meningitis or meningoencephalitis as most common manifestations in adults.

Currently, cleaning of fish slaughterhouses is performed manually, and often during night since the slaughterhouse utilizes two shifts to slaughter the daily quota of fish. The main objective of the cleaning task is to remove bacteria, biofilm and other contamination hazards. It is important to prevent growth of bacteria in the fish slaughterhouses.

The labor is time consuming and takes place in a harsh environment with a lot of chemical use. There is a high passage in the workforce. The current way of cleaning a fish processing plant is largely conceived by trial and error, and little formal research has been done other than the formal demands from Mattilsynet (Norwegian Food Safety Authority) stating that only approved disinfection aids are to be used [7], together with different cleaning companies having done their internal research. There are increasingly tougher quality demands both from customers and from governments, and there is a growing requirement for documentation of the processes of slaughtering fish, and therein the usage of cleaning chemicals and logging of cleaning procedures. The cleaning of equipment used in fish slaughterhouses is closely related to the fish quality, and eventual outbreaks of *Listeria* spp. is very unwanted and damaging both to the fish factory and the industry as a whole [8, 9].

As of today, the process of cleaning fish slaughterhouses is a costly process for the factories, with an average of 10 workers each night for 6 - 7 hours. Each worker is earning around 600,000 NOK (60.307 EUR, or 71 USD) each year due to a relative high basic salary level in Norway and additions to the salary due to nighttime work and doing work in hazardous environment.

Firstly, this paper will give overview of the Norwegian Aquaculture Industry in which the research in this paper is set as explained in the previous section. Then, some of the cleaning hassles that currently exist in the Norwegian Aquaculture Industry are presented in the two subchapters following the introduction. Chapter 2 is divided into six parts: 2.1 gives an overview of the theory backing the research method presented. Subchapter 2.2 describes how the research method is implemented and how the experiments presented are being conducted. 2.3 presents the work done around material choices in the Norwegian Aquaculture Industry and the link to EHEDG guidelines. Chapters 2.4, 2.5 and 2.6 presents and discusses results of design concepts related to functional requirements, surfaces and installation and other remarks regarding Design for cleaning, respectively. Finally, in chapter 3, conclusions and further work is presented.

2. Design for cleaning

2.1 Theory

"Design for X" is a method of focusing on a limited number of the most vital components of a design at a time [10]. Design for cleaning is introduced as a concept in product development, which focuses on making the product easier to clean. This is related to the operation phase of the life cycle of the product. This is an effort to keep focus on reducing cleaning costs and cleaning time in the operations of fish processing plants. This is builds on "hygienic design" in the sense that hygienic design is an evaluation of how well the design prevents a contamination risk after the equipment is built, whereas Design for cleaning is taking the cleaning process into consideration when designing the product with an end goal of making the cleaning easier, thus mitigating contamination risks.

The process of gaining knowledge about how to do the design changes could be said to be a form of experimental research with field experiments. An experiment is often used to validate a hypothesis [11], and the hypothesis which are being evaluated are defined as design concepts. The design concepts are tested in the field, in this case in several actual fish processing plants.

The European Hygienic Engineering Design Group (EHEDG) has released a document of Hygienic Equipment Design Criteria. It "describes the criteria for the hygienic design of equipment intended for the processing of foods. Its fundamental objective is the prevention of the microbial contamination of food products" [12], and consist of several guidelines divided into chapters regarding materials, functional requirements and hygienic design and construction.

2.2 Method

The guidelines proposed by Hauser *et al.*, [12] are reviewed and interpreted, in addition to considering the guidelines proposed from Nikoleiski [5]. They are then conceptualized into specific design concepts for a specific case-product for a specific OEM in the Norwegian Aquaculture Industry. The design concepts are derived by close interaction between the OEM and several fish processing facilities, combining the knowledge of both and taking the wishes from the fish processing facilities into consideration. Several stages of design reviews were crucial to reach end design concepts.

Virtual prototyping was used extensively in the design phase, and the most promising concepts were built in actual sized prototypes. The prototypes that were built were further tested at the fish processing facilities. The designs were evaluated and feedback from the fish processing facilities to the OEM led to further design enhancements and other concepts which again was tested and evaluated, in an iterative process for testing design concepts.

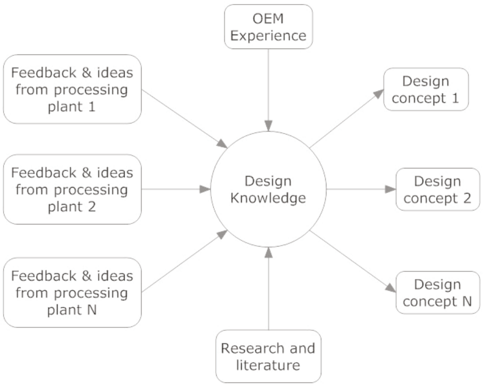

Figure 1. Concept development process

The design changes proposed came from several sources. Some changes came from one or several fish processing plants to the OEM, while other changes were a result from brainstorming internally in the OEM design environment. Even further ideas to design concepts came from reading books and research articles referenced in this paper.

In this case study, one particular product from the OEM is evaluated as previously mentioned. This is the conveyor product family, which has a lot of variants. During the work, the design was revisited from scratch. Design inputs came both from customers and the OEM, and inside the OEM both welders and fitters were involved in the design process together with both experienced and new engineers. The proposed changes apply to all of the different conveyors inside the product family, and the focus has been on changes that could be implemented in several products and are more of a general type of change. Following will be a description of how an OEM in the Norwegian Aquaculture Industry has changed their equipment design in an attempt to interpret the design guidelines proposed by EHEDG.

2.3 Material choices

The guidelines presented in EHEDG chapters 4.1 General, 4.2 Non-toxicity, 4.3 Stainless steel and 4.4 Polymeric materials are all concerning material choices: they should be non-toxic, mechanically stable, corrosion resistant, and have a surface finish that makes them suitable. Due to demands from the industry, these guidelines must be followed, and thus they are also followed in the case product. All parts of the design concepts are made either in AISI 304 or AISI 316 steel, or where applicable polyoxymethylene (POM) or polyethylene high-density (PEHD) 500 polymers. This is compliant with EHEDG chapters 4.3 Stainless steel and 4.4 Polymetric Materials which lists the best materials to use when the ease of cleaning is the focus, and these materials are also non-toxic, corrosion resistant and are mechanically stable.

2.4 Functional requirements

The guidelines presented in EHEDG chapters 5.1 Cleanability and decontamination, 5.2 Prevention of ingress of micro-organisms and 5.3 Prevention of growth of micro-organisms are concerning functional requirements with regards to cleaning and contamination that equipment should adhere to.

EHEDG chapter 5.1 Cleanability and decontamination states that equipment should be easy to clean. EHEDG chapter 5.2 Prevention of ingress of micro-organisms and chapter 5.3 Prevention of growth of micro-organisms in the same document discusses issues of ingress of microorganisms and preventing them to grow.

The first design concept regards simplifying the cleaning of surfaces. When two surfaces are bolted together, as shown in Figure 2, ingress of water happens in all gaps due as shown in Figure 3 . This water could be contaminated with microorganisms, which clearly violates 5.2 and 5.3.

This problem is further illustrated in Figure 4, which shows an old design from an OEM. It is evident from the figure that the surface area in contact here is large, and much water could be trapped in between which gives microorganisms a place to grow.

Equipment such as shown in Figure 3 is seldom disassembled for cleaning, and when it is there is often biofilms formed in between the surfaces. Disassembly for cleaning is very costly. It is a time-consuming task which requires skilled workers, and shutting down a fish processing plant presents a severe loss in revenue.

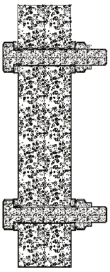

Figure 2. Contact surfaces

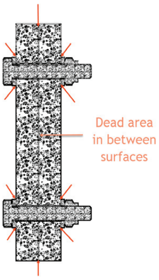

Figure 3. Contact surfaces ingress points

Figure 4. Contact surfaces on real product

A new concept is illustrated in Figure 5, which introduces bushings to separate the two surfaces and reduce the area in contact. Only the small area of the bushing is in contact.

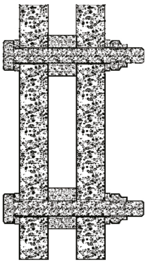

Figure 5. Bushing between surfaces

It is the OEM's experience that a bushing length between 5 and 7.5 mm is sufficient to clean in between the surfaces, and the bushing should have a diameter no less than two times the bolt diameter. Feedback from several fish processing plants and examination from the OEM states that overall this reduces the amount of water trapped and biofilm formed, despite the increase in the number of ingress points, marked in red on Figure 6 Bushing between surfaces ingress points, and thus this concept is a good approximation to EHEDG chapters 5.2 and 5.3.

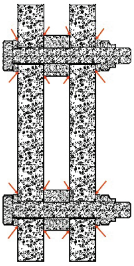

Figure 6. Bushing between surfaces ingress points

The concept is further illustrated in Figure 7 and Figure 8, which shows bushings between contact surfaces on two different products, marked by orange rings. By allowing only small surface areas of contact in general, one could prevent the growth of microorganisms and bacteria build-up.

Figure 7 shows bushing being used on a different product than a conveyor, illustrating that the design concept is not limited to conveyors only.

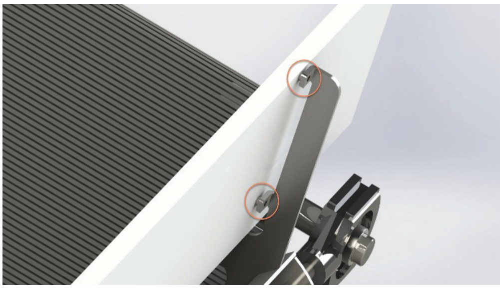

Figure 7. Bushings on real product

Figure 8. Bushings on real product

2.5 Surfaces and installation

EHEDG chapter 6.2 Surfaces and geometry states that product contact surfaces must be free for imperfections, direct metal joints should be welded, misalignments must be avoided, corners should be rounded and threads should not come in contact with food. The surfaces should tolerate the product and the necessary detergents and disinfectant, and be non-absorbent.

Continuous welding is used everywhere possible, and as discussed previously, where it is not possible, bushings are used to minimize the surface area of contact. Other improvements to welding is to create welding points instead of long continuous welds, if the structure allows it. This reduces bending of the steel due to welding, and shortens production (welding) time. The welding point could be 2 cm in length for instance, and then creating a gap between the surfaces. In the OEM's experience, a gap of 7.5mm is a gap that allows thorough cleaning between the two parts being joined together, whilst still keeping the structural integrity in place. This is illustrated in Figure 9.

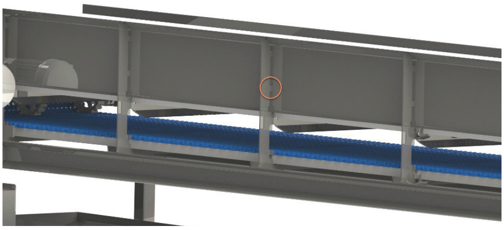

Figure 9. Welding points

Welding points such as these must be designed with close attention that the structural integrity is sufficient. For a load bearing weld, other lengths may be preferred, the 2 cm suggested is used for a non-load bearing weld outside the structural framework of the conveyor.

Equipment must be designed such that water drains off and risk of condensation on and inside equipment should be avoided according to guideline EHEDG chapters 6.4 Drainability and lay-out and 6.5 Installation respectively. Previously, square pipes have been used to great extent for structural framework for machines and equipment. The flat surface on top often gathers potentially contaminated water. This is illustrated in Figure 10.

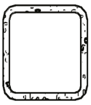

Figure 10. Square closed profile

This is avoided by flipping the square tube 45 degrees, creating a diamond-shape. However, the processing plants in the Norwegian Aquaculture Industry have been demanding round profiles/tubes for some time, illustrated in Figure 11. A round tube allows water to drain of very effectively and is widely used. Closed profiles, whether round or square, must be welded shut in the start and end. It is the OEM's experience that these welds will have microscopic pores in which microorganisms could ingress and bacteria growth will happen inside.

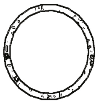

Figure 11. Round closed profile

A design concept improving this is shown in Figure 12. An open profile eliminates the risk of condensation during installation, and the ingress of microorganisms.

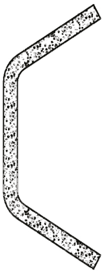

Figure 12. Open profile

The difference between a closed profile and an open profile in actual conveyor products is shown in Figure 13 and Figure 14, respectively.

Figure 13. Closed profile in real product

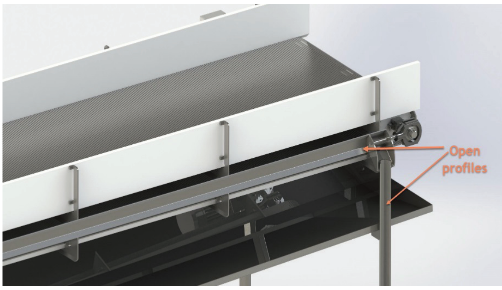

Figure 14. Open profile aon real product

Pay attention to the bearing installation in Figure 12 compared to in Figure 13. When using a closed tube, the way the bearing is fastened is by mounting a threaded bar into the profile, which allows ingress of bacteria into the pipe. Ingress of bacteria happened in the lower tube in the picture above too, due to microscopic pores in the weld as discussed previously, but not as much as in the top tube. Pay attention that an open profile also is used for legs and sidewalls.

2.6 Other remarks regarding design for cleaning

The surface finish/surface roughness should have an acceptable Ra-value according to 6.3 Surface finish / surface roughness. The materials used in this industry satisfies these requirements and thus the design concepts also comply with these guidelines. Welding is used extensively for steel-to-steel contact, with an emphasis on making the welds continuous and smooth, corresponding to guideline 6.6 Welding. Bolted connections are avoided where possible, to the extent it does not imply a significant increase in production costs.

When introducing the open profile like pictured in Figure 12 and testing it at actual processing plants, the feedback was that the profile was more of an obstacle to cleaning inside the belt than the tube or pipes which were used previously, because the open profile had to be larger than the equivalent closed profile due to stability and strength. This violates Guideline 5.3 to some extent, even though the goal, avoiding build-up of microorganisms inside closed profiles, is reached with the design. The design was further enhanced by moving the open profile below the belt, further down towards the floor in the construction, in Figure 15.

Figure 15. Improved open profile

In products where an open profile framework is not ideal due to strength and stability, the OEM have switched from using square tubes to round tubes. These do not gather as much water and has better drainability, as suggested in EHEDG chapter 6.4 Drainability and lay-out. They are also preferred from customers since a rounded tube is friendlier for the operators inside the processing plant when it comes to bumping into them. The transition between the two is shown in Figure 16 and Figure 17.

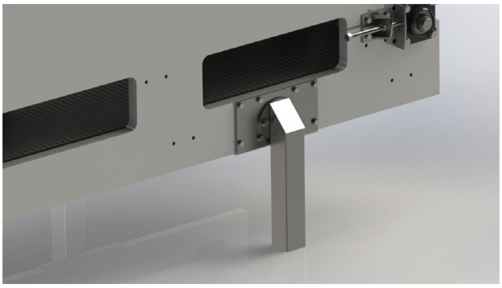

Figure 16. Square closed profile on real product

Figure 17. Round closed profile on real product

The results are further compliant with Machinery Directive 2006/42/EC. As discussed in [5], the EHEDG Guidelines are stricter than the Machinery Directive. All the changes make the equipment easier to clean and disinfect, and they minimize the risk of any substances accumulating or entering the machinery.

The design principles introduced has in some cases led to increased production time and cost, because using custom profiles requires more labor than using off-the-shelf available profiles, such as tubes and pipes. In addition, the profiles must be continuously welded to other parts of the steel frame, requiring more welding than what is necessary with standard profiles. However, due to the reduced cleaning time and effort needed, the fish processing plants are willing to pay the extra cost for these design improvements. Adding bushing to reduce surface area contact also requires more labor than mounting the two surfaces together directly, but also this is an acceptable increase in production cost and time.

3. Conclusions

- Design for cleaning is a new way of thinking about design in the Norwegian Aquaculture Industry. It focuses on making products easier to clean in their day to day use, thus reducing the risk of bacterial build up which could contaminate consumer products. It is important to notice the balance between Design for cleaning and design for some other parameter, as discussed in "Design for X" literature. In Design for cleaning, production time and cost is not the focus, the value added for the customer in the operational phase with a Design for cleaning focus far outweighs the potential drawbacks.

- The principles from EHEDG applies to all equipment and machines, and in this paper only a case study on conveyors has been done. Further work related to Design for cleaning is to implement the lessons learned from this case study to other products which are important to clean as well. Machines and equipment which are in direct contact with the end consumer product are the most important to keep a Design for cleaning focus on, since it is here a potential poorly cleaned area does the most damage (causes contamination to the end consumer product).

- Feedback from processing plants to the OEM states that a "Design for cleaning" mindset when designing processing equipment provides considerable customer value for the processing factories, as such design concepts directly saves cleaning time, and thus money. It also reduces the potential for bacterial outbreaks and contamination which is always a big concern.

- Further work could also be done to EHEDG Guidelines, in that some of the concepts and guidelines could be further clarified by illustrations and sketches, such as the ones that have been presented in this paper. This would provide valuable clarification of the principles discussed and remove doubts in how to design equipment for industries where hygiene is critical.

Acknowledgement

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Visualization Support for Design of Manufacturing Systems and Prototypes – Lessons Learned from Two Case Studies

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Abstract

This paper presents two case studies in which a framework for classifying the needed Level of Detail, Level of Accuracy and Level of Recognizability for 3D-scanns are used to 1) support installation of a robotic system for cleaning of fish processing lines and 2) support a retrofitting engineering project. Both cases are set in the Norwegian Aquaculture Industry. In Case 1, effort is done to develop a robotic cleaning solution for fish processing plants, due to a need to rationalize and automate the process. The chances of errors in the manual cleaning process is large. 3D-scanning is successfully used to create a solid model of processing equipment which in turn is used to create a cleaning path for the robot. In Case 2, the point cloud from 3D-scanning is used to check a planned layout of a retrofit project against the actual processing plant. Typically, such retrofit projects take more time and costs more money than initially planned because of unforeseen rework is necessary. This often is a result from poor or missing documentation of the existing processing plant. During the project, several errors were discovered in the planned installation due to missing or wrong information about the existing plant.

Both cases show that point clouds from 3D-scans greatly enhances communication, can aid in getting rid of design errors in the planning phase and can help shortening installation and commissioning times. 3D-scans are also beneficial when developing robotic simulations in complex environments. The framework helps in classifying the needed amount of work for 3D-scanning projects based on what the needed output is, thus potentially mitigating unnecessary resources being spent on either the scanning itself or post-processing of scan-data.

Keywords: 3D-scanning; point cloud; retrofit; simulation; robotic cleaning

1. Introduction

This paper presents two case studies in which 3D-scanning is used to improve processes in the Norwegian Aquaculture Industry.

A challenge when modernizing and rationalizing fish processing plants (FPPs) is the layout and complexity of the plants. 3D-layouts are now the industry standard, but earlier, FPPs were often designed using 2D-layouts. Creating up-to-date layouts of current FPPs is a labor-intensive job with traditional tools, which often result in inaccuracies [1]. Unforeseen complications, often resulting from the inaccuracies mentioned, during installation or lack of accurate data during design phases can result in changes that are not captured in as-built layout documentation. To make matters harder, each plant has its own unique design with regards to layout, size and height, and they are often modified extensively through several years of operation, normally without capturing documentation of the changes in overall plant layouts. This creates a gap in the spatial data available

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for most FPPs which results in a high risk of wrong input during planning phases of retrofit projects. A large part of the problem will also be the information that is not captured during planning but needed later during the design phase of a project.

FPPs are often situated far from the offices of the equipment providers, and the FPP may be a fishing vessel which in extreme cases only docks once each year. Faulty or missing plant layouts causes costly errors when doing retrofit.

The high throughput of fish in current FPPs are challenging for installation and commissioning of complex equipment/retrofit. Most plants run two processing shifts, 5 days a week throughout most of the year. This makes the allotted time window for installation and commissioning very short. Violation of the allotted installation time due to errors during planning costs a lot of money, with fish prices in excess of 5 USD per kg [2]. In addition, doing such retrofitting into existing FPPs are accompanied by increased risk of bacterial contamination [3–5] and the threat increases with installation time.

This creates a need for an efficient method to capture the complex layout and infrastructure which exists in processing plants whilst enabling an engineer to check measurements in the post-planning phase. 3D-scanning of processing facilities is foreseen to be a good approach to solve these trials.

Another challenge to develop more efficient processing plants is to automate more of the processes on the plant. Automating more of the processing has been a research effort over several years [6–9]. One such opportunity is automated cleaning of the processing facilities. It is tough manual labor, consisting of repetitive tasks in an environment which is unpleasant due to spray fog and chemicals, often at undesirable working hours. Errors occur during the manual cleaning process, making it unstable. Cleaning must be done each day due to food safety [10,11], and failure to do so could lead to bacterial outbreaks which could be harmful for humans [12]. Foodborne diseases are also costly [13] with $1.4 trillion per year in costs related to foodborne illness worldwide, e.g. cleaning is important from both a “safe-to-eat” and an economic standpoint.

A novel robotic cleaning solution is proposed to solve the challenges [14,15], whilst adhering to hygienic design principles [16] to avoid introduction of bacterial risk. It consists of a customized robot manipulator, a custom-built rail to carry the manipulator in the processing plant and a design which allows customization of the solution to different processing plants. It also has a custom control system [17], which is based on 3D-simulation of the manipulator and rail to create cleaning paths. This 3D-simulation requires 3D-data of the equipment which is to be cleaned in order to program the manipulator. Because of the already mentioned complexity and challenges of the processing plants, a method of capturing the layout in high accuracy is needed. This level of accuracy is not possible to obtain through traditional methods due to time and cost constraints.

Visual aids, such as CAD and point clouds may be of help in such cases [18,19]. Off-line programming of robots (simulation) has also been proven useful in shortening commissioning times [20–22] and discover design errors [23], because a lot of the initial errors are discovered and fixed already in the virtual stage.

This paper will utilize a newly developed framework [24] to determine requirements of Virtual Factory Layouts (VFLs) for the two cases. VFLs must be modeled in just enough detail to fit their purpose, and this paper will apply the framework to explore the two different needs of details for two different purposes. Specifically, this work will investigate if the framework is suitable for a 3D-simulation application and planning of a retrofit installation.

2. Method

Level of Detail (LoD), Level of Accuracy (LoA) and Level of Recognizability (LoR) from Eriksson et al. [24] is used to define properties and quality, and by combining features or levels from these classification areas, clarity should be provided of what the 3D-scan shall deliver as output. In the same work, the authors classify three purposes of having a VFL: Knowledge transfer, Layout management and Simulation, which are covered by the three levels. Each of the levels can also be divided in several sub-areas. LoD describes what a virtual object can be used for and features included are: As-is, Moveable objects, Measurable footprint, Measurable 2D distances, Measurable 3D-distances, Object kinematics, Order of stations, Material flow. Regardless of the use of a VFL, a defined accuracy is needed, and LoA options consists of: Very coarse, Coarse, Medium, Fine, Very fine. For a VFL to fulfil its purpose, the receiver must understand what the VFL illustrates, and a LoR-level must be decided on. LoR includes features such as: Object name/no, 2D-area, 3D-block, Color, Shapes and features highly significant for object, Shapes and features significant for specific objects.

The cases will have two different applications of the 3D-data captured from 3D-scanning and will thus have different requirements for output.

2.1. Case 1 – 3D-simulation

A prototype of the cleaning robot discussed in Introduction was built. A test room was built to enable close to full-scale testing of the custom robot. Due to the multidisciplinary aspect of the problem studied, a full system prototype was built. Virtual tools is not suitable to test all the facets, although analytical prototypes in virtual tools were used on parts of the system [25]. Due to the mentioned challenges related to spatial data, the test room was scanned to mimic a retrofit installation of the robotic cleaning system.

The VFL requirement in this case is Simulation, but cleaning processes need less accuracy than traditional robotic simulation processes, such as robotic welding.

2.1.1. 3D-scanning of the test area

The test area is approximately 5x8 meters and is seen in Fig. 1. It consists of typical fish processing equipment, a frame to suspend the custom robot system in and the custom robot system itself. It is scanned using a Faro X130 HD scanner, with a total of 6 scans. 4 scans would have been enough, but to ensure sufficient accuracy and detail needed, two extra scans were made.

2.1.2. Post-work with the scan data

The scans were imported into Autodesk Recap to be combined into one large point cloud. This point cloud was exported into 3D Systems' Geomagic Design X as a .E57-file where it was further processed to a mesh. This was further developed on inside Geomagic Design X to build solid models which can be exported into any CAD-software platform. The hybrid model of mesh and solid can be seen in Fig. 2. The solid models were exported as .STEP-files and imported in Visual Components to serve as both a placement reference for the robot base, and a geometry to link the cleaning (robot) path to, see Fig. 3.

2.1.3. Use – 3D-simulations

The model was used as a reference model for the simulation program when generating a robot cleaning path using Visual Components. A picture of the simulation environment is shown in Fig. 3 in chapter 3.1.

Fig. 1. Picture of test room with equipment.

2.2. Case 2 – Retrofit

A running retrofit project of new equipment and layout change into an existing processing plant serves as a full-scale prototype case for installing the robotic cleaning system. The requirement in this case is Layout Management. From the LoA, a medium to fine accuracy is needed. The machines must be recognizable, and, in some cases, the new equipment will be fitted to existing machines, making it necessary to have a fine accuracy. Also, from LoA, 3D-blocks are needed, and for specific objects, shapes and features are significant (e.g. where new equipment will interface with existing). The planned new layout is modeled based on existing 2D floor plan data.

2.2.1. 3D-scanning of the test area

The tested area is approximately 1800m^2, and is filled with existing processing equipment, machines and other installations such as pipes and HVAC-components. The same laser scanner as in Case 1 was used, but it took 12 scans to cover the area. The scans were done without color to save time, and with less accuracy, detail and coverage compared to Case 1.

2.2.2. Post-work with the scan data

The 12 scans were imported into Autodesk Recap and merged into one larger point cloud. The scans were not processed any further in Autodesk Recap. The resulting point cloud is shown in Fig. 4, and it was overlaid the planned CAD-layout and aligned using the pre-existing columns in the factory, visualized in Fig. 5.

2.2.3. Use – Design review

The hybrid model was used for reviewing the proposed layout and evaluating the fit between the existing building infrastructure and equipment and the new proposed layout of equipment.

3. Results

In both cases, the 3D-scans provided visual aid which helped communication. We saw that even though the cases were different, the same method could be used. Two different levels of VFLs are developed for two different use cases with different levels of requirements. The framework presented in Eriksson et al. [24] can be used to establish the necessary requirements for using point clouds.

3.1. Case 1 – 3D-simulation

The solid model obtained from the 3D-scan was used to create new robotic cleaning paths, reducing the needed iterations to create a complete cleaning program with higher accuracy than achieved before. Solids were also used to check for collisions between the robot and existing equipment, which in earlier run throughs of the testing had happened due to the inequalities between the virtual and the physical prototype.

In relation to the framework, the following features were important from the three different classification areas:

Table 1. Features related to a VFL for simulation.

Level of Development	Level of Accuracy	Level of Recognizability
As-is	Fine	Color
Measurable 3D- and 2D-distances		Shapes and features highly significant for object and specific objects
Measurable footprint		

Surfaces are created based on the mesh of the point cloud. The solids are created by typical CAD-software operations.

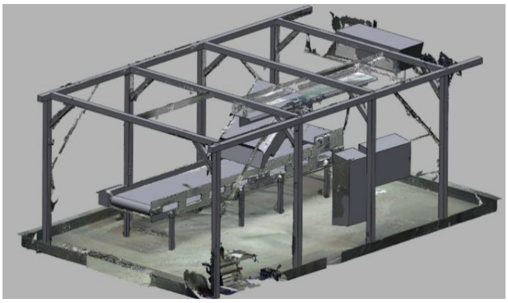

Fig. 2. Hybrid model of point cloud and solid models.

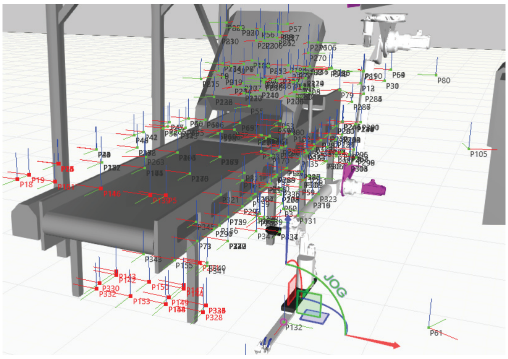

Fig. 3. Solid model from 3D-scan used in 3D-simulation software.

The points in Fig. 3 are displaying the x-, y-, and z-coordinates and rotation against the x-, y- and z-axis for the Tool Center Point of the robot manipulator.

3.2. Case 2 – Retrofit

The point cloud was used for a design review of a planned retrofit installation. In relation to the framework, the following features were important from the three different classification areas:

Table 2. Features related to a VFL for retrofit (layout management)

Level of Development	Level of Accuracy	Level of Recognizability
As-is	Coarse	3D block
Measurable 3D- and 2D-distances		Shapes and features highly significant for object and specific objects
Measurable footprint		

The point cloud aided in communication and knowledge transfer in the project, and the hybrid model with both the planned new layout and the point cloud of the existing processing facility showed several occurrences where the planned new layout interfered with existing infrastructure or layout. The list is exhaustive, and not all of them are presented in this paper, but a brief overview of some important issues is presented for illustrative purposes.

Fig. 5. Comparing fit with existing 3D building model with point cloud.

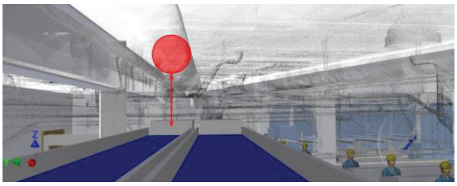

Fig. 6. HVAC-interference.

The area shown in Fig. 6 above, contains several building infrastructure elements like HVAC (heating, ventilation and air-conditioning) and roof drainage piping as well as cable trays. The double conveyor (in blue) was initially planned

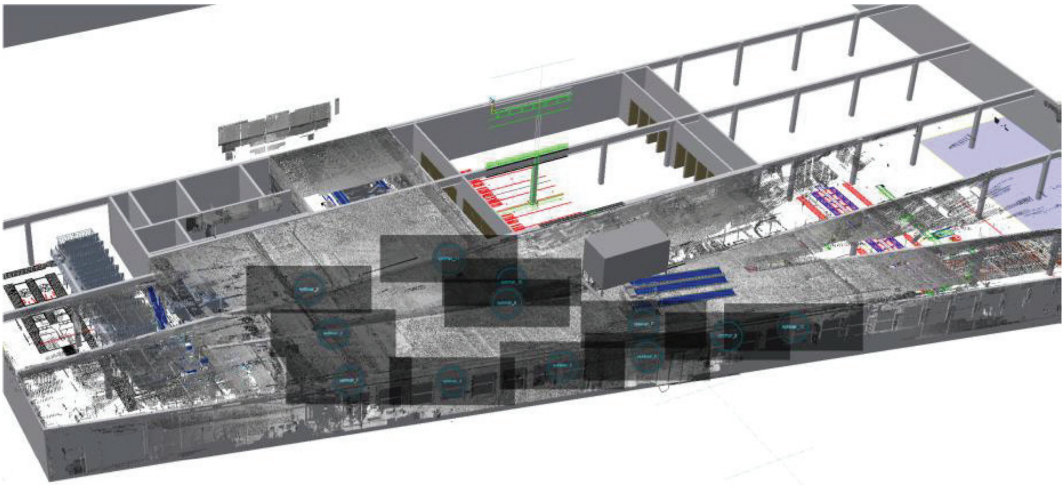

Fig. 4. 3D scan overlaid planned layout.

flush with the underside of the ceiling beam (to the left above the z-axis shown on the picture). A HVAC-pipe marked in red was in the way. After identifying the amount of changes required to the building infrastructure systems in this area to achieve this, it was decided to lower the conveyor line instead. These changes were not discovered from the initial 2D- and 3D-layouts used for planning.

Fig. 7. Walkway-issues.

In Fig. 7 above, a conveyor was situated in the red area. A walkway passes under this now, but the new conveyor (in blue) will be an obstacle for this walkway, and a new walkway must be planned.

In Fig. 8 a conveyor and tank are seen placed into the existing building structure. According to the building model and floorplan drawings, the conveyor and tank clears the obstructions but as illustrated in the figure, the placement and dimension of the wall is incorrect. The red-dotted line shows the needed new placement of the conveyor. The red circle indicates interference between a tank and an existing building column. During installation this equipment would be one of the first things to be installed due to the size of it. The consequence of modifying the installation to clear the obstructions would require the entire interconnected installation to be changed as well, potentially causing huge delay (the interference itself and additional modifications) if not identified before entering the installation phase of the project.

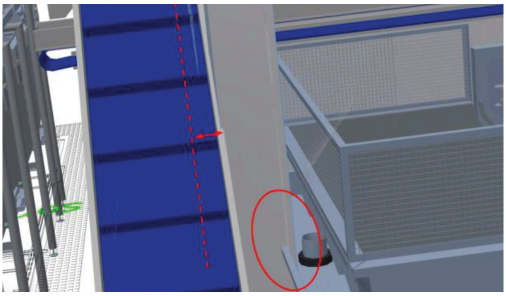

Fig. 8. Interference with infrastructure.

4. Discussion

Creating a solid model from a 3D-scan like in Case 1 required a lot of engineering hours despite the low complexity and small area due to the needed output of solid models. Intelligent and automated ways of reverse engineering of point clouds are emerging and will make this work easier in the future. Automatic generation of geometry based on point clouds has been a research topic for some time and still is [27,28]. Several software vendors are offering semi-automatic conversion from point clouds to solids through automated or semi-automated processes [26]. Such automated software was not utilized in this study. One should nevertheless be certain it is necessary before doing it due to the computational power required. In this case, only the equipment being cleaned was necessary to model in solids, and some time could have been saved.

Case 2 as presented in Fig. 6 illustrates a way 3D-scanning could provide additional value to processing facilities. The placement of lighting armatures seen in the upper right-hand corner are now captured, something that would not be surveyed by traditional methods. Since they now are known, the equipment provider was able to tell the processing facility that they needed to change the lighting armatures' location when the new processing line was put into the point cloud model. These sort of changes to infrastructure often happens during installation phase and have few or missing mechanisms to indicate necessity and as a result, the installation phase is often crowded of workers due to the high number of parallel "reactive" installation activities.

Grand-total for this case study, the total time estimated to be saved is estimated to be several weeks in rework, plus additional design optimizations were possible on the ground of a richer information basis. This amounts to a lot of money saved, both in man-hours and in additional parts needed (new parts, altered parts, discarding parts). The reduced time is also of importance and value for the FPPs, as such a time delay would impact their business significantly, due to the high throughput of the business discussed in Introduction.

Not all retrofit projects are suited for 3D-scanning. Some retrofit projects are so straight forward and low complexity, that it would be enough to use traditional measuring tape. Even though scanning time is not significantly high, the total added time of set up, scanning, post work of scan data adds more engineering hours than the traditional measuring tape. Some sort of threshold in complexity needs to be defined to make an informed decision of whether to do scanning of a planned retrofit project.

Nevertheless, 3D-scanning technology can help in retrofit projects by reducing the needed rework. It may even limit errors during new installations, as in some cases, the building infrastructure is not built as planned. These changes are often not discovered until processing equipment is being installed, and this also causes delays and rework. Building Information Models are often not containing the details of a facility as it was built [29]. 3D-scanning the new building infrastructure to validate its geometry may avoid errors. Discovering errors earlier in the process reduces the costs of those errors significantly. Informants from the Aquaculture industry in Norway estimated a 5x cost of errors during installation or production compared to discovering those errors in the sales phase of the project.

Some of the errors detected from the 3D-scan in case 2 may have been discovered regardless using only traditional methods, and as such it is hard to say exactly how much time is saved using 3D-scanning in this case. However, the use of a

3D-scanner does not add any significant time or cost during the planning phase, and as such it is seen as beneficial. Only two test cases are discussed in this paper. More testing of the framework is needed in the future.

5. Conclusion

Both cases benefited from 3D-spatial data derived from 3D-scans. 3D-scanning provides not only a visual aid but can also directly improve simulation, installation and commissioning processes. 3D-scanning also has a large potential in reducing uncertainty, rework and installation time for retrofit projects.

The proposed framework by Eriksson et al. [24] can be used to develop requirements in both cases and provide value of what output is needed. Developing clear understanding from all parties about what a point cloud/3D-scan will be used for will remove uncertainty for the surveyor and ensuring not spending more resources than necessary on any given 3D-scan data during reverse engineering stages. Understanding that in Case 2, knowledge transfer was the main aim, thus it was not needed to do solid modelling from the point cloud is such an important discovery. Discovering design errors during the planning of the retrofit was possible with only the point-cloud model as output. This saves time in developing the final output model. In contrast, more detail was needed in Case 1, and extra care was done to capture more details of the room by adding extra scans behind equipment, and it required further work on the output model. The features presented in the three different classification areas presented in the framework could be expanded and further refined in the future, maybe alongside a pre-project checklist to ensure the needed output is captured.

Both cases also reveal there is a potential for the technology to serve as a learning and cooperation facilitator for the larger cluster of involved stakeholders for aquaculture engineering projects. Through better identification of information, the aquaculture industry's ability as a whole can be improved in terms of meeting critical time windows in a harvesting schedule, or meeting go-live dates of newbuilds.

In the future, the framework may be expanded into a larger model of how to do 3D-scanning projects based on their use, and to further refine and develop which features are important in each of the three classification areas.

This work contributes to the application areas of the framework from Eriksson et al., and expands with suggestions of how to expand the framework.

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Prototyping installation and commissioning of novel a cleaning robot by using virtual tools – lessons learned

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Abstract

This paper presents a simulation study in which virtual product development tools are used to support the design of a novel robotic cleaning solution for fish processing facilities. The installation and commissioning of complex equipment in these facilities are challenging owing to the unavailability of accurate spatial data of the facilities; this generally results in delays. Delays causing unplanned stops are particularly undesirable in fish processing plants because processing facilities produce fish five days a week throughout the year. In this study, virtual tools such as 3D-CAD and 3D-scanning are utilized in product development processes to develop virtual factory layouts; these are used for simulation. These virtual tools are aimed at reducing delays during installation and commissioning of complex products in fish processing plants. The results reveal that the application of 3D-scanning and simulation technology in virtual factory layouts can reduce the installation and commissioning time for retrofitting manufacturing equipment, which are important aspects for reducing the risk of bacterial contamination in fish processing facilities. The results also reveal that virtual factory layouts, 3D-scanning, and simulation may enable further research in fish processing facilities, e.g., simulating new fish processing concepts without intervention in operational fish processing plants. Simulation and 3D-scan data aids product development processes by reducing time and uncertainty and by discovering design errors at an early stage.

Keywords: 3D-scanning; simulation; prototyping, fish processing; robotic cleaning

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1. Introduction

This paper presents a simulation study in which a novel custom-built robotic cleaning system is proposed to automate the cleaning process in fish processing plants (FPPs). The study is performed in the Norwegian aquaculture industry (NAI). In the product development (PD) process of the study, virtual tools such as 3D-computer aided design (CAD) and 3D-scanning are used extensively to create virtual factory layouts (VFLs) to perform 3D-simulations. These technologies are exploited to shorten the PD and implementation time. To the authors' knowledge, simulation studies are not commonly used to support PD activities; rather, they are used to fine-tune well established processes in the manufacturing domain and support decision making in production.

There are a few challenges that hinder the implementation of complex equipment in FPPs such as a robotic cleaning solution. Presently, FPPs are designed in CAD tools to create VFLs. However, a few years ago, most factories were designed using 2D-layouts, or even approximate sketches on paper. Developing updated layouts of current FPPs is a labor-intensive job with traditional tools, which generally results in inaccuracies [9]. Consider the complex geometry of machines, layout variations, and surrounding support structures in Fig. 2 and Fig. 3; it is evident that capturing accurate spatial data is challenging. The current industry standard is a tape measure or laser measuring tool and mobile phone photographs. In addition, unforeseen circumstances during installation or deficiency of accurate data during design phases can result in last-minute changes that are seldom fed back to ensure updated documentation of as-built facilities. This creates a

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deficiency in information with regard to the FPPs' as-built documentation. This renders the planning of the retrofitting of complex equipment challenging. The fact that each plant has its own unique design regarding layout, flow of raw-materials, size, and height increases the challenge.

Another challenge is the high throughput of fish in current FPPs. Most plants operate two processing shifts, five days a week throughout most of the year. This significantly shortens the time window for installation and commissioning of complex equipment: ideally between Friday night and Monday morning.

The testing and verification of products and equipment are generally conducted by original equipment manufacturers (OEMs) at their location. The environment in which the equipment is supposed to operate is harsh and challenging with regard to both fish residue and cleaning. In addition, each fish is unique, and operations for processing fish are more challenging to automate than operations for processing materials such as pieces of steel. In addition, the environment and the inherent geometry and behavior of fish are challenging for OEM's to replicate. This results in a deviation between what is feasible to be tested at the OEM's location and the performance required of the equipment in FPPs; it necessitates in-place adjustments after the equipment is installed in an FPP.

These challenges related to PD-activities are addressed through the simulation study presented next.

1.1. Simulation Study—Custom Robotic Cleaning System

Considering the likely growth in farming of salmonid fish and other aquaculture activities, efforts are required to rationalize and automate fish processing [1,2]. A potential area for automation is the process of cleaning FPPs. The current state-of-the-art cleaning process is manual cleaning at night; it must be performed each day after processing to mitigate bacterial contamination [3,4]. The tasks are repetitive and challenging manual operations in a humid operating environment with a spray fog of water and chemicals, as shown in Fig. 2.

Furthermore, the cleaning process is a time-consuming and expensive process for the FPPs; in addition, the cleaning results are subject to human, procedural, and/or operational errors [5]. Ineffectively cleaned processing equipment are likely to result in bacterial outbreaks, which in the worst case are likely to be lethal and result in significant economic losses for the FPPs from call-backs and embargos on the batch of fish with contamination [6–8]. In addition, a complete thorough washdown of the processing facility involving disassembly of machines and equipment for cleaning may be necessary; this is likely to result in a shut-down period. To implement an automated robotic cleaning system in FPPs, a few challenges related to its employment must be solved; these are presented next.

Cleaning is critical; this implies that prior to implementation, the proposed automated cleaning solution's functionality must be tested and verified thoroughly to minimize intrusion and reduce the implementation time. Furthermore, a proposed solution must be designed such that it does not impose new threats of bacterial contamination; this implies that its design must ensure hygiene and cleaning convenience [10,11].

Overall, this creates a need for a flexible and scalable automated cleaning solution that adheres to hygienic design principles. A method is also required to capture the factory layout data to adapt the solution to the facility. In addition to a method for testing the cleaning performance of the above-mentioned solution, a method for testing the installation and commissioning process must also be developed.

To solve the challenges related to rationalizing the cleaning process of FPPs, a novel hygienic robotic cleaning solution is proposed [5,6]. This solution is designed to adhere to hygienic design principles to prevent further increase in the risk of bacterial build-up, and to be capable of being customized to each FPP and being operational in the harsh environment that occurs during cleaning. The system consists of a custom built six degree of freedom (DOF) robot manipulator on a custom-built rail and trolley, with interfaces to existing equipment and systems in fish factories (Fig. 1). The control system is custom made to complement the manipulator [7]; it is based on 3D-simulation of the manipulator and rail to develop cleaning paths.

Fig. 1 Robotic system in the test facility (prototype lab)

To measure the system's accommodation to the challenges presented, a test environment is constructed for the PD-process, both for the custom cleaning robot and for incorporating the whole implementation process of the complex equipment in the PD-process.

Fig. 2 Operational environment of robotic cleaning system

Fig. 3 Typical slaughter line in an FPP

2. Product Development of Fish Processing Equipment

Ulrich and Eppinger, [8], proposes a generic PD-process; it is presented in Fig. 4.

Fig. 4 Generic PD-Process (from [8])

Owing to the above-mentioned challenges related to the installation and commissioning time as well as the unfavorable environment within FPPs, the PD of the fish processing equipment involves certain special considerations related to the environment in which the developed equipment would be situated and to the raw material upon which the machines would operate (biological masses of fish).

An OEM's prototyping efforts for FPPs are similar to the generic PD-processes observed in similar/other industries. Principally, this implies designing in 3D-CAD, construction, and testing. Testing is generally conducted at the OEM's location(s); however, it involves substantial logistics to obtain fish for testing (generally dead fish, which are sorted out from production and go directly to waste). Additionally, the quantities of fish used in testing are typically low; therefore, equipment adjusted based on test-fish need not function effectively on the variety that is present at FPP. Furthermore, it is challenging to replicate the real-world processing environment. This creates a void in the capability to perform testing in near-real environments, which necessitates numerous adjustments when the equipment is installed at fish processing facilities. H. Birkhofer states in *The Future of Design Methodology* that rapid prototyping can be achieved both through virtual and physical systems [9]. VFLs and simulation technology may aid in bridging this void and enable rapid virtual PD.

3. 3D-Laser Scanning and Simulation

3D-CAD, 3D-laser scanning, and simulation (in 3D) are technical tools used in VFLs. A brief introduction to 3D-scanning and simulation is presented next.

3.1. 3D-Scanning

Manual physical measurements (which are time-consuming and generally result in low accuracy) followed by extensive CAD-work is the traditional method of constructing virtual representations of production systems. Non-contact 3D imaging technologies such as terrestrial 3D laser scanning can be used to capture spatial data of real production systems and develop accurate and realistic virtual representations with high accuracy and speed. Generally, several scans are conducted to gather complete spatial information of large or complex areas. These are generally aligned and combined into a dataset using software. Such datasets, or point clouds, comprise several millions of points; thus, filtering is required to reduce the data size [10,11].

3D-scanning originated from surveying, although it has increased traction in several engineering applications and scenarios such as heritage documentation, medical applications, crime scene documentation, industrial quality control, robot navigation, and machine vision [12–14]. The raw data file containing the point cloud information is generally in a manufacturer-proprietary format. Unless the downstream processing software supports these, conversion into a standardized point cloud exchange format is required; moreover, several data formats are available.

Using 3D scanning utilities rather than manual documentation methods can improve job site safety [15]. In certain cases, the efficiency of the data collection processes can be increased by approximately four times [16]; it has also been observed to have significantly improved information density and accuracy over traditional 2D documentation such as floor plans. The use of 3D point clouds for visualization and decision support purposes has demonstrated that the communication between different engineering and project management departments can be improved. Costs and project durations can be reduced by improved visualization, and potential design errors can be eliminated in the early phases of project execution. The information also enables better decision making. 3D-scanning has also been established to be beneficial in improving off-line robot programming (simulation) [17].

3.2. Simulation

Off-line programming of robots is generally called simulation. This has been utilized to identify and repair design errors [18] and test equipment virtually to shorten the commissioning times [19–21]. Virtual testing of production flows, material handling, and robot welding are examples of discrete event simulation (DES) applications. DES tools are used to simulate events at discrete points in time inside virtual environments and models; moreover, these events emulate events that could occur in a physical production system [22] to evaluate and predict the real world system's behavior. For a while, DES models have been common as 2D visualizations; however, as CAD-capabilities have grown, DES visualizations in 3D have become more common [23,24]. Visualization DES models are important for validation and verification processes and for aiding the communication of results and attaining a common understanding of both models and results [22–24].

Numerous methodologies for carrying out DES studies have been developed [22,25]; however, all of them include a combination or derivative of the steps proposed by [26]:

1. Problem formulation
2. Model conceptualization
3. Data collection
4. Model building
5. Verification and Validation
6. Analysis
7. Documentation
8. Implementation

A few of these steps may be omitted, a few could overlap, and a few could be iterated. Overlap can occur when data collection continues during model construction owing to time constraints; or, iterations may occur if the analysis fails to satisfy the requirements of the problem formulation [22]. Simulation will be used as synonymous to DES for the remainder of this article. The steps presented previously will be used to review the simulation study of the robotic cleaning system.

4. Description of Simulation Study

The simulation study is the actual PD-process of the robotic cleaning system. To replicate an actual implementation of the robotic cleaning system, the whole process is prototyped; this implies that the workflow of the planning, installation, and commissioning of the robotic cleaning system is replicated, tested, and evaluated.

The envisioned workflow for the installation and commissioning of a robotic cleaning system is shown in Fig. 5; here, two workflows are likely depending on whether the cleaning system is to be installed in a new or an existing factory. In the case of a new factory, the system may be included during the planning phase; meanwhile, for an existing factory, it must be added to existing equipment and infrastructure. Adding such complex systems to existing facilities is challenging and relies on spatial data of existing equipment and infrastructure; these may be challenging to obtain as explained in previous sections. In the most challenging occurrences, no existing CAD-layout of the facility is available. For this simulation study, a facility without CAD-documentation is selected to mimic such cases. Prototyping the method of implementing such a system is a method of mitigating risks and overcoming obstacles relating to the actual implementation of such systems. 3D-laser scanning is used to obtain spatial information and 3D-simulation of the reach, functionality is used together with 3D-CAD to adjust the systems. Both are crucial technologies to minimize the installation and commissioning times.

This whole process is emulated by developing a small-scale lab environment with typical equipment that is necessary to removing bacteria from; a fish stunner [27] and a conveyor used for gill cutting. These machines are covered in fish blood, fish remains, and fish slime after processing, as shown in Fig. 3; furthermore, this equipment is situated at the start of a fish processing line. Bacterial contamination from this equipment could spread to the remaining processing facility if not cleaned properly.

The machines in the test facility only had 2D layout drawings and not 3D-CAD drawings. Around the equipment, a frame of 100 × 100 × 5 mm steel beams are installed in the facility based on approximate skethes. The custom robot manipulator and accompanying rail system are modeled, constructed, and suspended in the frame.

As shown in Fig. 5, VFLs are important in numerous processes, and could include including a CAD-model, simulation model, or point cloud model, or any combination. Simulation must be used extensively to verify the correctness of the planned installation with regards to reach and performance. Marginal adjustments may be necessary in the custom cleaning robot manipulator depending on the particular facility; simulation aids in identifying the need for such adjustments. 3D-scanning may aid in assessing the actual layout with respect to the planned layout and in determining the geometry required to develop simulation models.

The whole room is scanned using a FARO X130 HD laser scanner [28]. Six scans are carried out; the details are presented in Table 1. These are imported into Autodesk ReCap [29]; then, they are combined into a dataset and refined using the automated *Cleanup*-feature in ReCap. This is exported as a ply-file and imported in Geomagic Design X [30]; here, it is meshed using Design X's built-in features for automated mesh creation to create surfaces [31,32] that can be sketched upon. The sketches are used to create solids through standard CAD-modelling operations.

The solids are exported as a STEP-file and imported into Visual Components (VC) [33] for simulations. The custom cleaning robot's kinematics is developed in VC; moreover, the robotic cleaning path is developed manually in VC, with the solids visually aiding the identification of the locations to be cleaned and the prevention of collisions.

The steps in a DES-study presented earlier will be used to verify if simulation and 3D-scanning can be used to prototype the installation and commissioning process of intricate equipment in complex building infrastructures.

Owing to the custom control system, simulation of the robot to generate cleaning paths and robot movements is the only feasible method for producing a program for the robot to follow. A tech pendant, commonly found in mist industrial robot manipulators, is not developed during this work.

Table 1 Simulation study outline and 3D-scan details

Scan/simulation study	Details
Purpose	Visualization. Evaluation of workflow. Creating solids. Geometry check. Simulation
Volume of interest	7 × 5 × 3 m = 105 m^3
Scans	6
Time to scan	Approximately 1 h
Scan data size	Approximately 900 mb

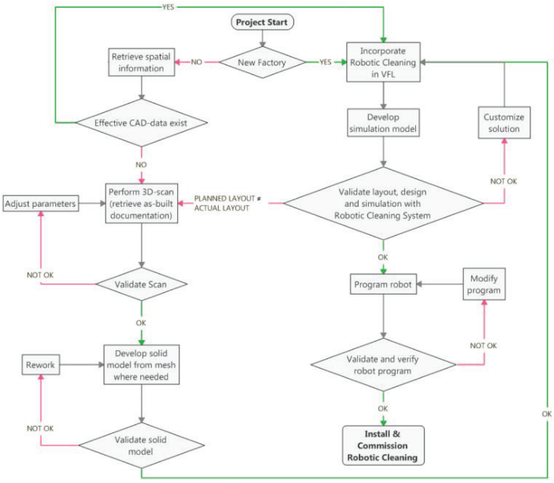

Fig. 5 Workflow for implementing robotic cleaning solution

5. Review of Simulation Study and Lessons Learned

The specific PD-process for the custom robot cleaning system terminates at testing and refinement at a TRL-6 level [34] because of the abrupt increase in difficulty to implement such equipment in a real fish processing facility. Substantial learning emerges from the prototype and the prototyping activities.

Compared to traditional testing of prototypes in this industry, the test facility enables more realistic testing, with the robot spraying water and cleaning chemicals on the soiled equipment. Testing with bacteria would not have been feasible without the test facility. It enables both the measurement of cleaning results and the replication of the humid environment typically observed during cleaning in fish processing facilities. This test verifies that 1) the robot could operate in similar environments, 2) the robot could clean as effectively as humans can [6], and 3) the process of developing realistic VFL for simulating existing processing plants without updated layout documentation is feasible.

Following the study steps presented earlier, Table 2 presents the steps carried out and lessons learned in relation to those steps in this study. An X under "used" indicates that the 3D scan data is used in the corresponding simulations study step.

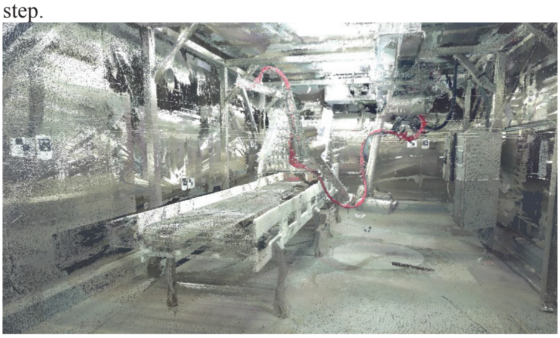

Fig. 6 Point cloud of scanned lab in Autodesk ReCap

Table 2 Addressed steps in simulation study.

Simulation study step	Used	Comment
Problem formulation		The problem formulation is carried out prior to capturing scan data. In this demonstration, the whole test lab is required for a successful simulation study. In other cases, the simulation problem to be studied may serve as a guide to what should be scanned.
Model conceptualization	X	Scan data is utilized directly as shown in Fig. 6 to plan installation and, to a certain degree, marginally alter the layout and the custom cleaning robot. 3D-scanning may result in less travel to sites because the 3D-scan data may be used for planning and familiarization of the facility. This is true also for simulation, as it is a typical problem in the industry that commissioning consumes an excessively long time compared to the customers' expectations. Both technologies are also likely to aid OEM's in saving money because planning both the installation and the testing of the functionality of complex systems can occur virtually at the OEM's site. It is also more convenient to get more individuals involved and provide ideas and feedback if such VFLs exists; this is generally not feasible owing to the remote locations of most FPPs.
Data collection		No further data is collected in the study. However, it was discovered that 3D-scanning and can aid in reducing the time-on-site compared to traditional surveying and commissioning methods; this is beneficial with regard to the risk of bacterial contamination [35,36]. Simulation reduces the number of iterations from those generally required to commission complex systems in existing plants [20]. An important observation is that in general, measurements that were not initially considered became important during later planning stages; moreover, these are readily available from the 3D-scan.
Model building	X	Scan data is used to position the cleaning system and represent the lab-equipment and surrounding infrastructure. The scan data is also used to construct solid models of equipment to test for collision and to plan/program the cleaning path for the robot, as shown in Fig. 7 and Fig. 8.
Verification & Validation	X	The simulation program is used to verify the design and functionality of the custom robot. Additional marginal errors are discovered in both the design and cleaning path; these are fixed. It is also used in the physical test and thus used for validation.
Analysis	X	The physical placement of the robot is iteratively evaluated considering obstructions from the surroundings, reachability, and, collision. The study is also used to create and evaluate the effectiveness of the cleaning path in several iterations. The accuracy provided is sufficient in the case of cleaning simulation and path planning. However, it is evident that without adequate knowledge of the equipment that is scanned, constructing accurate 3D-models from the scan data is challenging.
Documentation	X	The 3D-scan is used as lab documentation in this case and is likely to fill the void left by missing documentation, which is generally the case in the NAI.
Implementation	(X)	The simulation model is used for implementing the lab environment during tests of the custom cleaning robot.

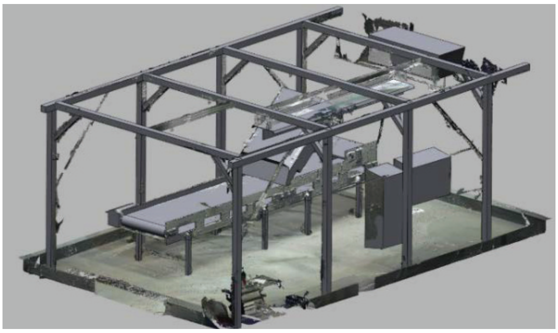

Fig. 7 Hybrid model of point cloud, mesh, and solid models in Design X

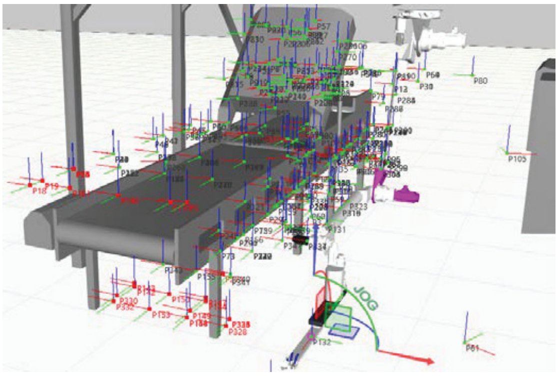

Fig. 8 Solid model from mesh used for simulation in VC

In relation to the generic PD-process from Ulrich and Eppinger, the following lessons are learned in this simulation study:

Table 3 Lessons learned in relation to the generic PD-process

Step	Lesson learned
Planning	Planning the lab-concept is convenient owing to the available 3D-scan data. It enables testing of different layouts and configurations of the lab. Simulation enables testing of the reach during planning.
Concept development	The concept is mainly developed based on sketches, which are refined with CAD-drawings in conjunction with 3D-scan data.
System-level design	The system level design is supported by 3D-scan data and simulation. The system design (specifically, the interfaces between the rail, trolley, and manipulator arm) is changed based on simulations.
Detail design	The detailed design of the manipulator arm is changed based on testing in simulations.
Testing & refinement	The simulation environment, mainly based on CAD-data and supported by 3D-scan data, enables the testing of the reachability of the manipulator in conjunction with the rail. The simulation study also provides some feedback of whether the equipment is cleaned or not, based on the reachability and aim, together with information about collision; the cleaning paths are adjusted accordingly. Moreover, the 3D-scan data is a significant aid in this regard as it enables collision assessment of the geometry absent in CAD-models.
Production ramp-up	This stage is not performed in this study

6. Discussion and future work

The work described in this study examines the combined use of 3D-scanning, CAD, and simulation. Although there is no control or reference group, the previous studies referred to in this work yielded largely identical results. The observations of this study are likely to be transferrable beyond this study to other industries and other countries. It is challenging to say how much longer it would take to develop effective robotic cleaning paths without an accurate solid model derived from 3D-scans. The use of both 3D-scanning and DES is new in the NAI.

3D laser scanning is not utilized to its full potential for simulating production systems, as indicated in previous research. This study indicates that some of the problems could be the different software packages required to attain the industrial performance of 3D-scans and the creation of meshes/solids for use in simulation environments. Substantial converting between data types is required to achieve the objective. In particular, developing effective solid models is challenging, both from an engineering and a hardware/software perspective. The engineer must understand the products to be capable of recognizing features in the product after meshing and be familiar with the facility to determine what is important to retain and what can be deleted.

The steps for creating a mesh and further solid models are not strictly necessary in this study. The point cloud could have been used as a point cloud in this work. However, efforts are undertaken using 3D-Experience (a simulation software from Dassault Systemes [37]) to use the solids for automated path planning based on surfaces, as an alternative to VC in parallel with constructing a simulation model in VC. Although this is not successful in this study, it may be necessary to attain the actual industrial performance of the workflow from a non-existent CAD to the completed robot program.

Although this is a small simulation study, the benefits of conducting 3D-scanning to obtain an accurate representation of the layout are evident. 3D-scanning is a suitable tool for enabling simulation in complex environments whose 3D-layouts cannot be developed within a reasonable amount of time using conventional methods.

The capability to perform simulation enabled fewer iterations for developing a complete cleaning path than those without the capability; this is owing to the mentioned benefits in Table 3. This is likely to be valid for other complex product developments as well. In the case of fish processing, the situation is challenging; the behavior of a fish is challenging to model; therefore, it is likely to be challenging to develop simulation models for fish processing (e.g., handling operations).

6.1. Future work

In relation to cleaning of FPPs, simulation and 3D-scanning exhibit significant potential for aiding further developments. However, advancements are required to develop simulators specifically for cleaning. Developing the capability to “color” cleaned areas and potentially logging the amount of chemical/water used will be highly beneficial; it will enable the testing of different cleaning paths and their rating based on cleaning effectiveness and speed. Technology may be transferred from the simulation of spray painting and used for this application.

As an extension of this, further work is also required for developing effective and efficient methods for capturing spatial data for use in a cleaning simulator. The state-of-the-art efficient method for simulating robotic spray painting involves clicking on the surface to be painted; this generates a spray pattern. This could be used for cleaning as well, although it would require an efficient method for developing solid bodies or surfaces from point clouds.

The aquaculture industry does not have large-scale lab facilities for conducting more close-to-real testing of fish processing. The lab in this study is orchestrated specifically for this purpose. A larger, more general lab for fish processing would enable development of more advanced fish processing machines and techniques; this is because it is challenging to obtain permission for highly intrusive tests at available processing facilities. Having a dedicated lab environment to test the robot is crucial in this study. Conducting such tests in a regular OEM workshop environment would not have yielded the same learning and may have limited the amount of testing with bacteria and water/chemicals. Efforts should be made to develop large scale labs to enable the testing of novel fish processing methods and machines.

In conjunction with this, developing simulation models of fish behavior, texture, friction, etc. is likely to open new opportunities for simulating fish processing; this could further increase the rate of innovation in fish processing. Simulation may aid in other research challenges in the fish processing industry as well, such as one-piece-flow, material handling tasks, and other developments of robotic and automated operations.

Further work is required to provide capabilities of incorporating biological challenges into the simulation environment; this requires multi-domain simulation capabilities. In this specific case, this would require the development of simulation models for bacteria behavior and their reaction to different chemicals, amongst a range of other simulation models. Although this is challenging, it would be beneficial for industries combining the technology and microbiology domains.

Further studies are also required to develop procedures and best practices for combining simulation and 3D-scanning, as it is at present tedious to obtain the correct formats and software packages to operate together. The size of scanned 3D-data is also an issue, notwithstanding the continuously increasing storage capacity and improved machine hardware and performance. Efforts should be undertaken to develop one or several formats that shrink the data size and to improve the feasibility of working with VFLs, point clouds, and simulations in one software package to streamline the process. This will also help streamline the related PD-process.

7. Conclusions

This simulation study demonstrates that 3D-scan data can be used to develop better simulation models and improve robotic programming, thus verifying previous research. A visual representation of data such as 3D-scans provides enables communication and facilitates project planning. The capability to take measurements as required is a highly significant benefit of 3D-scan. The capacity to use 3D-scans in VFLs to plan layouts by combining CAD and point cloud data is highly valuable; this is particularly so in the NAI owing to the challenges with regard to layout data and reducing the amount of time and number of times needed on site planning. This will aid in mitigating the risk of bacterial contamination while conducting a survey of the facility. The simulation in this study may be used to evaluate the functionality and effectiveness of the cleaning path of the robotic cleaning system, in addition to reducing the on-site commissioning time. This is an important aspect of fish processing facilities in general, as reduced commissioning time will further mitigate the bacterial contamination risk. The process of developing realistic VFL for simulating existing fish processing plants without updated layout documentation is feasible. Both simulation and 3D-scanning technologies enable more rapid product development in the study presented; moreover, virtual product development exhibits a significant potential for application in the development of complex products, to a wider extent than that at present.

Acknowledgements

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HYGIENIC STANDARDS AND PRACTICES IN NORWEGIAN SALMON PROCESSING PLANTS

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Abstract

The farmed salmon industry is important economically for several countries with Norway as the main producer constituting 53% of the world total. Bacterial contamination of salmon products may occur during processing, constituting potential life-threatening health hazards (e.g. listeriosis). The *L. monocytogenes* threat and thus strict legislation on ready-to-eat salmon products (i.e. smoked salmon) makes plant cleaning and hygiene important issues in the salmon industry. The present situation regards measured hygienic quality (i.e. cleanliness as means of total bacterial counts and the presence of *L. monocytogenes*), and hygiene standards and procedures in Norwegian salmon processing plants were investigated through visits and interviews at plants. The aim of the study was to identify potential sources of cross-contamination through the processing line and critical points for cleaning.

Four salmon processing plants were visited during the autumn of 2015. A total of 91 samples were collected. Sampling was performed during full operation from: gutting machines and drains, water tanks, conveyor belts, floors, and from round fish (skin and gills) using Sodi-box cloths, FloqSwabs and water samples. Total aerobic bacteria and *Listeria* spp. were enumerated by plate counting and the presence of *L. monocytogenes* confirmed.

From 91 samples, 6 were positive of *L. monocytogenes*. *L. monocytogenes* was found in one gutting machine at 2 out of the 4 plants, occasionally on floor, drains, and conveyor belts, once in a water tank, but not on ungutted fish. There was not found any correlation between the level of *Listeria* spp. and the total bacteria count ($R^2 = 0,026$, n = 30). Even though the levels were low, the findings of *L. monocytogenes* in processing equipment may potentially pose a threat to food safety. *L. monocytogenes* is a ubiquitous bacterium that is easily introduced from different sources. The main challenge is to hinder plant colonization through improved hygienic practice and hygienic design.

Key words*: Salmon, Listeria, Hygiene, Hygienic design, Cleaning, Processing plants.*

1. Introduction

Approximately 80% of the salmon farmed and slaughtered in Norway is exported unprocessed beyond slaughtering and gutting to other countries, where final processing and further distribution takes place. The consequence of this is that Norway loses a potential valorization of the salmon raw material, including by-products and side streams.

For the Norwegian salmon industry to fully exploit the salmon raw material, there is a need for modernization in the industry, in order to be competitive regards customs barriers and cheap labor. This implies fully automated lines including the whole process from: killing, bleeding, gutting, filleting and secondary processing, and by-product harvesting and processing. Through automation, one may limit the present use of buffer tanks for: cooling, rinsing and grading of the fish, and rather implement hygienic controllable lines focused on following single individuals through all processing steps. The use of fully automated processing will lead to reduced human labor, increased profitability, and allow for full processing in Norway. The advantages will be better quality control in all steps, reduced transport costs and increased valorization. In such a process, hygiene is an important element, especially considering *Listeria monocytogenes* and other pathogenic bacteria that can establish in slaughterhouses and processing plants. An automated processing design handling fish individually may prevent bacterial cross contamination. It is important to secure good hygienic practices to achieve sustainability in the salmon processing industry.

The purpose of the present study was to identify sources of bacterial contamination along the present processing lines. The identification of critical steps and spots may allow for improved hygienic design connected to killing, slaughtering and processing in processing lines facilitating automation. The present situation regards measured hygienic quality (i.e. cleanliness as means of total bacterial counts and the presence of *L. monocytogenes*), and hygiene standards and procedures in Norwegian salmon slaughterhouses were investigated through sampling and interviews at four plants along the west coast of Norway.

1.1 The Salmon processing line

At present, the typical salmon slaughterhouse can be schematically outlined as in Figure 1.

Live farmed salmon is pumped either directly from the well boat transporting the salmon to the slaughterhouse, or from a sea net pen adjacent to the slaughterhouse, temporarily holding the salmon. Inside the slaughterhouse, the fish first enters a live chilling tank, with temperature close to 8 ^{0}C. The purpose of this tank is to lessen stress, to some extent sedate the fish, and to facilitate further processing by rectifying the fish. Typical residence time in this tank is 45 minutes.

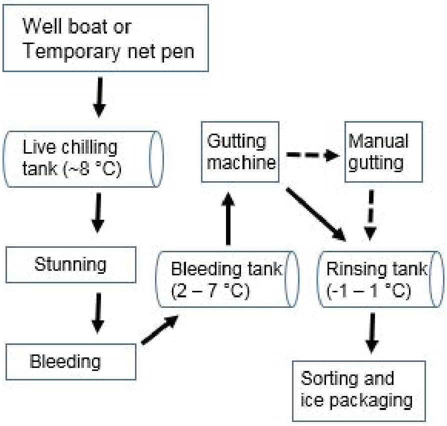

Figure 1. Typical salmon slaughterhouse operations

The fish is then stunned, normally in an electrical stunner [1]. The majority of Norwegian slaughterhouses do not have the live chilling tank, in these cases fish is pumped directly from the well boat/temporary net pen, and conveyed to the electrical stunner. Conveyor belts then transport the fish to the bleeding station, where the throat pulmonary artery is cut, in most cases manually. Bleeding out proceeds in seawater tanks with temperature of 2 - 7 ^{0}C and residence time 30 to 45 minutes. Next, fish is mechanically gutted, typically using a Baader® machine. A small fraction of the fish is bypassing the gutting machine and subject to manual gutting. This is due to deviant size (too small or big for the gutting machine). After gutting, the fish are conveyed to a rinsing tank with temperature of -1 - 3 ^{0}C. After approx. 25 minutes, depending on the final product format, fish are decapitated, filleted, or packed round. Fish, regardless of end-product, are finally packed on ice and stored before transport.

The Baader machine is according to plant operators a problematic source of recontamination, e.g. with *L. monocytogenes*, which is frequently isolated from the machine. Cleaning of the gutting machine is complicated since it is constructed of several small movable parts, lubrication points and vacuum suction, in addition to hard-to-reach areas for the cleaner. For thorough cleaning and disinfection, the gutting machine must be disassembled, which is not practically to do after each use, but rather as a part of e thorough clean-down of the processing plant, typically performed a couple of times per year. Other areas less accessible for daily cleaning, like under conveyor belts and other areas not directly accessible, may also be problematic. Conveyor belts and the transition zones between plastic and steel may form a good starting point for the formation of biofilms, especially when worn [2].

The water tanks in salmon slaughterhouses, especially the bleeding- and rinsing tanks, are easily contaminated with organic material, i.e. blood, and to a lesser extent skin mucus, scales, and gut content. *L. monocytogenes* is frequently observed in water high in organic material [3], and is able to survive at least 6 days in water with salmon blood at 2 - 7 ^{0}C [4]. The water tanks consist of tube systems and helixes that may function as a niche for *Listeria* spp., and due to the large size, helixes and nozzles, full control of *Listeria* decontamination may be difficult. Based on this, it was hypothesized that the tanks may act as reservoirs and even facilitate the persistence of *L. monocytogenes*. However, after analyzing the tanks in four slaughterhouses, we did not find conclusive evidence for this hypothesis with respect to *Listeria*. A more general conclusion is rather that fish and seawater entering the slaughterhouses have undetectable levels of *L. monocytogenes* and that contamination occurs mainly during processing after the gutting step.

1.2 Cleaning, legislation and internal routine controls

The salmon slaughterhouses are cleaned at nighttime after one or two shifts of production (depending on season and demand). This cleaning typically consists of an initial rough flushing with clean water to get rid of fish residuals and blood before it starts sticking which it will do if it starts drying. Then the area is foamed with acid or alkaline based soap and sprayed with disinfection chemicals in various forms. All cleaning is done by manual labor at present. Depending on the size of the plant, several workers walk around flushing the surfaces with a hose. Typically, the operators on the different machines do a crude flushing of the equipment and machines with cold water when their shift is finished. Then the cleaning shift comes in when the production is finished for the day. The cleaners spray on soap-foam, which covers the different machines and production surfaces. This foam should work for some time before water is sprayed on to rinse off the soap. Mostly hot water is used, but it should not be too hot because that will make it difficult to rinse of protein coatings. The last step is to apply disinfectants to inactivate microorganisms. The disinfectant is normally left to vaporize until the production starts again in the morning. The time estimated for the cleaning shift for flushing, foaming, rinsing and disinfection of the area defined as the 'slaughter line' (approx. 60 m^2) in a specific slaughterhouse slaughtering > 100 tons of salmon per day is 3.5 hours. The slaughterhouses have differing routines for disassembly of equipment and full plant wash downs. This largely depends on the type of equipment and amount of use.

The Norwegian Food Safety Authority must approve: establishment, operation, moving and change of operation at slaughterhouses and processing plants. Application for approval must be followed by a description of internal control systems securing sufficient hygiene and prevention of spread of disease, and plan for journaling and documentation. The contagious hygiene demands are general, and simply stating that it must be secured that personnel, workwear, equipment, machines, used packaging etc. does not constitute a hygiene risk, there must be a barrier between by-products and wastewater, and all processing water and wastewater must be disinfected [5]. Norwegian food industry is further subject to the EU enforced Regulation (EC) 178/2002 [6], laying down the General Principles and requirements of food safety, and later Regulation (EC) 852/2004 [7], for Hygiene of foodstuffs, and other related Regulatives and Directives as reviewed by Kakurinov *et al.*, [8]. The food safety that applies to the consumers is in the end secured through general food safety regulations. The recent EU-rules sets a limit of 100 cfu g^{-1} at the end of the shelf life in products where *L. monocytogenes* is able to proliferate, like for example cold smoked salmon (CSS) [9]. There is no formal demands on the internal control systems except that it must be understood to secure sufficient hygiene and prevent spread of disease, and it is supervised, controlled and legislated by the Food Safety Authority. Systems approved can include a program for daily environmental and food product sampling for *Listeria* and coliform bacteria and less frequent (weekly - monthly) sampling for e.g.: total bacterial count (TBC), Salmonella, etc. in: products, specific equipment, ice and water. The samples are either analyzed in the slaughterhouses own laboratories on site, or they are sent to extern laboratories. It is very much in the slaughterhouses and their owners own interest to have a strict hygiene control because there will be serious consequences if there should be recalls or shut down, both economically and on public relations.

2. Materials and Methods

Four salmon processing plants (designated A, B, C, D) were visited during the autumn of 2015. Sampling was performed during full operation using Sodibox cloths (Sodibox, La Forét-Fouesnant, France), FloqSwabs (Copan, Italy), and water samples. Sampling was performed according to Table 1.

Approx. 2500 cm^2 were sampled with Sodibox cloths, and 25 cm^2 with FloqSwabs. Water sample volumes were 0.5 to 1 L. Only round ungutted salmon was sampled (skin samples behind the gills and above the centerline, and gills). Samples were stored at 4 ^{0}C and processed within 24 h. Sodibox cloths were placed in stomacher bags (Seward Medical, UK), suspended in 250 mL of buffered peptone water (Oxoid) and homogenized in a Starblender LB400 stomacher machine (VWR) for 3 minutes. For detection of *L. monocytogenes*, 45 mL of the homogenate was filtered onto a 0.45 μm Mixed Cellulose Ester (MCE) filter with a diameter of 47 mm. The MCE filters were placed onto *Listeria*-selective Brilliance agar plates (Oxoid), and incubated for 24 h at 37 ^{0}C. Colonies suspected to be *L. monocytogenes* were transferred to new Brilliance plates and incubated as above. Presumptive *L. monocytogenes* on the secondary plates were again transferred to sheep blood plates (Oxoid) to observe for hemolysis, and confirmed to be *L. monocytogenes* by using the API Listeria kit (BioMerieux) according to the manufacturer's instructions.

Water samples was filtered and assessed as above, except that samples containing much blood and other organic material was prefiltered with a Steriflip vacuum-driven filtration system (Millipore, USA) with a 20 μm pore size. FloqSwab samples from ungutted fish skin and gills were transferred to 15 mL Falcon tubes prefilled with 5 mL buffered peptone water (Oxoid) directly after sampling. FloqSwabs were left to resuspend by shaking (250 rpm) at room temperature for 30 min.

Table 1. Sampling scheme

Plant	Type of sampling	Sampling location	Amount of samples (positive for *L. monocytogenes*)
A	Sodibox cloth	Drain after stunner	1
		Drain before gutting	1
		Floor by gutting machine	1
		Conveyor belt after gutting machine	1
		Gutting machine	2
		Drain after gutting	1
	FloqSwabs	Fish skin	5
		Gills	5
		Gutting machine	3
	Water	Live chilling tank	1
		Bleeding tank	1
		Sea net pen	2
B	Sodibox cloth	Table before bleeding	1
		Drain after bleeding	1
		Gutting machine	2 (1)
		Floor by gutting machine	1
		Conveyor belt after gutting machine	1
		Conveyor belt before sorting	1
		Sorting table	1
		Floor by drain, packaging area	1
		Sorting cubicle, wall	1
		Conveyor belt in packaging area	1
	FloqSwabs	Fish skin	5
		Gills	5
		Gutting machine	3
	Water	Bleeding tank	1
		Leakage in drain between gutting machine and rinsing tank	1
		Rinsing tank	1 (1)
C	Sodibox cloth	Conveyor belt after gutting	1 (1)
		Conveyor belt after bleeding tank	1
		Gutting machine	1 (1)
		Floor by drain between live chilling tank and bleeding tank	1
	FloqSwabs	Fish skin	2
		Gills	2
		Gutting machine	3 (1)
	Water	Live chilling tank	1
		Bleeding tank	1
		Rinsing tank	1
D	Sodibox cloth	Wall by stunner	1
		Conveyor belt after manual gutting	1
		Gutting machine	2
		Conveyor belt after gutting	2
		Floor by gutting	1
		Floor in packaging area	1 (1)
	FloqSwabs	Fish skin	5
		Gills	5
		Gutting machine	3
	Water	Swim-in stunner	1
		Bleeding tank	1
		Rinsing tank	2
		Well boat	1
Total			**91 (6)**

and then aliquots of the liquid were plated directly on Brilliance plates and assessed as above. Gill samples were only analyzed for the presence of *L. monocytogenes* and not quantification of bacteria.

For enumeration of total aerobic bacteria in Sodibox cloths and Floqswabs, aliquots of the homogenates were spread plated onto Plate Count Agar (PCA; Oxoid). Water samples were filtered onto MCE filters and placed on PCA plates. PCA plates were incubated for 48 h at 30 ^{0}C.

After sampling, the operators in charge at each plant was given a questionnaire with the following 12 questions as an e-mail attachment (translated from Norwegian):

1. What temperatures (^{0}C) are in the water tanks inside the slaughterhouse?
2. How often is the water in the tanks changed?
3. How is seawater rinsed before use?
4. From what depth (m) is seawater taken?
5. How many persons work per shift in production (inside the slaughterhouse including packaging area)?
6. How many shifts per day?
7. How much (tons) salmon are slaughtered per day?
8. Is salmon entering the slaughterhouse via sea net pen or well boat?
9. How is the processing plant cleaned at the moment?
10. Do you have procedures for disassembly and washing of all machines and equipment (how often)?
11. What microbiological control do you apply (i.e. daily/weekly sampling, amount of samples of water, equipment, floor etc.)?
12. What is the most challenging area with regards to *Listeria* control?

The questionnaires were filled in within two months and delivered back by e-mail.

3. Results and Discussion

Results of *L. monocytogenes* detection are shown in Table 2 and 3 divided on premises and sample type, respectively.

The level of presumptive *Listeria* spp. is shown in Figure 2 (installations) and Figure 3 (water tanks). Total bacteria counts are shown in Figure 4 (Installations), and Figure 5 (water tanks). Note that the dimensions in the y-axis in Figures 2 and 3 are cfu per m^2 and L, respectively as opposed to cm^2 and mL in Figures 4 and 5.

The questionnaire-based surveillance is presented in Table 4.

Table 2. Results of *L. monocytogenes* detection per plant

Plant #	Total samples	Positive for *L. monocytogenes*	% positive for *L. monocytogenes*
A	24	0	0
B	27	2	7.4
C	14	3	21.4
D	26	1	3.8
Total	91	6	6.6

Table 3. Results of *L. monocytogenes* detection divided by sampled item

Sample type	Total samples	Positive for *L. monocytogenes*	% positive for *L. monocytogenes*
Installations	42	5	11.9
Fish skin/gills	34	0	0
Water	15	1	6.7
Total	91	6	6.6

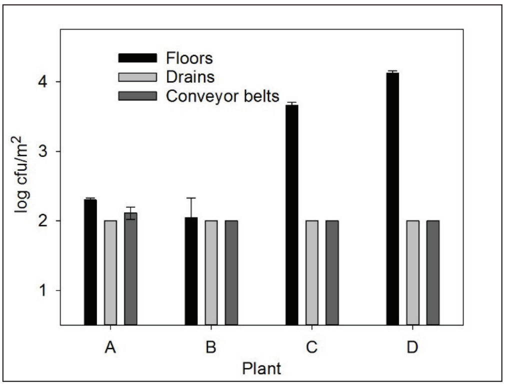

Figure 2. Presumptive *Listeria* spp. on surfaces and drains in salmon slaughterhouses. The dotted line denotes the detection limit of log 2 cfu/m2

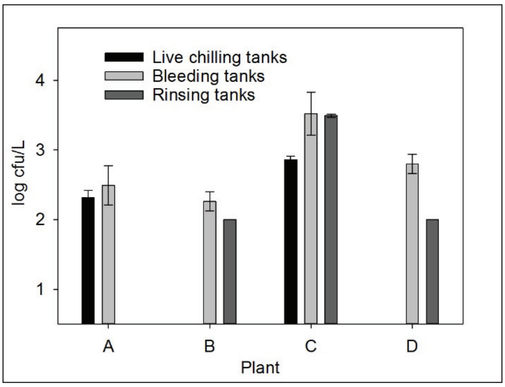

Figure 3. Presumptive *Listeria* spp. in water tanks in salmon slaughterhouses. The dotted line denotes the detection limit of log 2 cfu/L. Plant A did not have rinsing tank(s) and Plant B and D did not have live chilling tanks

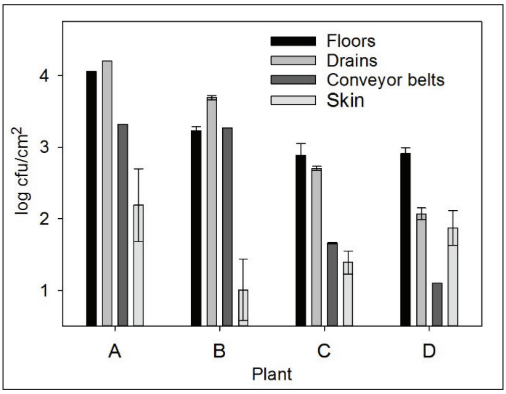

Figure 4. Total aerobic bacteria on surfaces and drains in salmon slaughterhouses, and on skin of ungutted salmon

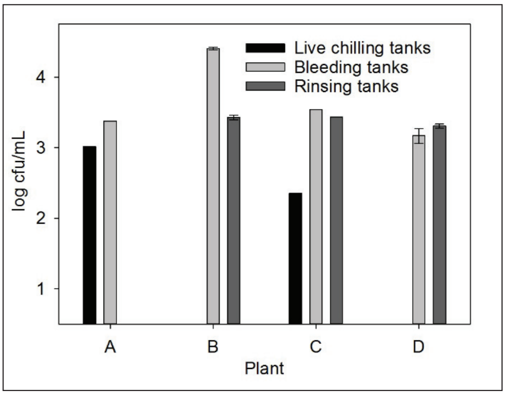

Figure 5. Total aerobic bacteria in water tanks in salmon slaughterhouses. Plant A did not have rinsing tank(s) and Plant B and D did not have live chilling tanks

After linear regression of 30 samples positive of *Listeria* spp., there was no correlation between the amount of presumptive *Listeria* spp., and the total aerobic bacteria count ($R^2 = 0.026$). However, we were not able to distinguish *L. monocytogenes* from presumptive *Listeria* spp. as defined by characteristic growth on *Listeria* selective Brilliance plates (Oxoid), so that *L. monocytogenes* is only reported as positive or negative as verified by API-typing, and not quantified. Anyway, we were able to identify the closely related, but non-pathogenic *L. welshimeri* and *L. innocua* in one of the gutting machines in plant B, and in floor samples from plant C and D, respectively. The results of presumptive *Listeria* spp. quantification implies that *Listeria* spp. other than *L. monocytogenes* were comparatively frequent. It should also be noted that *Bacillus* spp. was found to grow with similar characteristics on the Brilliance plates. Although these could be readily disregarded by microscopy and the presence of spores, we cannot rule out that they have interfered with the analysis.

Of the 91 samples collected, only six were confirmed positive for *L. monocytogens*, and out of these, three were from gutting machines, and one each from the floor in a packaging area, conveyor belt after gutting machine, and a rinsing tank (Table 1 - 3). This means that *L. monocytogenes* was found only at the site of gutting, or after gutting in the processing line. This underpins that gutting machines, under conveyor belts, and drains are problematic areas for *Listeria* control as pointed out by the plant operators (Table 4) and that they are hard-to-reach spots for cleaning.

The present study did not sample the processed products, but it is shown that 5% of Norwegian retail CSS is positive of *L. monocytogenes* [10], and the mean prevalence in retail CSS worldwide is close to 10% [9]. In the EU in 2015, 3.9% of ready-to-eat (RTE) fish, 2.5% of RTE meat, and 1.1% of cheese were *L. monocytogenes* positive [11]. It is well known that *L. monocytogenes* is a ubiquitous bacteria, and can very easily be transferred to various surfaces within a processing plant. Its saprophytic behavior allows it to decay moist plant material, and soil environments may be an important reservoir for this pathogen [12]. *L. monocytogenes* is very rarely isolated, however, from clean (unpolluted) seawater and from fish bred in pure water, meaning that the many positive samples from salmon products clearly indicates contamination during processing [13]. The present study is in accordance with this view, since no *L. monocytogenes* was found on skin or in gill of ungutted fish, and was only observed in a water tank after gutting and at the end of the slaughtering line (Table 1 and 3). Recontamination in the processing plant is often seen as the main problem [14, 15]. Some slaughterhouses may be colonized by *L. monocytogenes*, while others are free of the bacteria. Thus, raw material from particular producers may act as vectors for bacteria into smokehouse facilities, and it is therefore important to avoid *L. monocytogenes* contamination of slaughterhouses and slaughtered salmon.

Mechanical systems, e.g. gutting machines (Table 4) are difficult to clean and disinfect. Recontamination is therefore difficult to prevent. Autio *et al.*, [14] showed that by removing colonized equipment followed by thorough disinfection of remaining equipment and processing area by including hot steam, hot water, and hot air (80 °C) were effective measures for eliminating *L. monocytogenes* which was established on the processing line. Some bacteria, including *L. monocytogenes*, are capable of forming biofilms on material like for example stainless steel, which is widely used in processing equipment. Cells in this condition may be resistant against sanitary measures and thereby able to establish itself in processing lines [16]. Vogel *et al.*, [15] concluded that since salmon, although to a lim-

Table 4. Summary of surveillance based on questionnaire to plant operators

Questions*		Plant			
		B	C	D	
Water tanks	Q1	0 - 2	0,5	Normally 0 – 2	Bleeding tank: 2 - 7, Rinsing tank: -1 - 2
	Q2	Daily	Daily	Daily	Daily
	Q3	UV treatment	No rinsing	Filter and UV treatment	UV treatment
	Q4	30	ca 70	ca 35	ca 60
Production	Q5	17-18	22 on 1st shift, 15 on 2nd shift	ca 40	40-45
	Q6	2	2 (April 15th - June 15th). 1 (rest of year).	1	2
	Q7	210-215	ca 150 when two shifts, ca 90 when one shift	130-150	300
	Q8	Well boat	Usually net pen	Usually net pen	Well boat
Cleaning and microbiology	Q9	Daily flushing, foaming, flushing, disinfection. The plant is washed down 4 times a year.	Daily foaming, circulation wash and disinfection	Daily acid/alkaline chemicals and disinfection	Daily flushing, alkaline foam, flushing, disinfection. Switching regularly to acid foam.
	Q10	Fixed program. Depending on type of equipment	No fixed program	Fixed program. Semiannually	Fixed program. Depending on type of equipment
	Q11	Daily: Environmental sampling with regards Listeria (approx. 30 samples) and coliform bacteria. 3 times a week: ice sampling Weekly: Salmonella, sulfite reducing bacteria, Clostridia, and TBC. Water intakes (fresh and seawater), and from ice machine.	Daily skin and environmental sampling (sent to extern laboratory).	Daily: Product sampling, and equipment according to plan. Sampling of water 4 times per year.	Daily: Listeria in production environment and product. Twice a week: ATP sampling Weekly: Listeria and TBC in clean areas. Monthly: TBC and coliform bacteria in fresh/sea water and ice.
	Q12	Areas less accessible for daily cleaning with risk of biofilm formation (gutting machine, under conveyor belts, transitions between plastic and steel, etc.)	Gutting machines	Gutting machines	Vacuum systems and gutting machines, floors and drains.

Legend:
*: Q1: What temperatures (ºC) are in the water tanks inside the slaughterhouse?; *Q2: How often is the water in the tanks changed?; *Q3: How is sea water rinsed before use?; *Q4: From what depth (m) is sea water taken? ; *Q5: How many persons work per shift in production (inside the slaughterhouse including packaging area)?; *Q6: How many shifts per day?; *Q7: How much (tons) salmon are slaughtered per day?; *Q8: Is salmon entering the slaughterhouse via sea net pen or well boat?; *Q9: How is the processing plant cleaned at the moment?; *Q10: Do you have procedures for disassembly and washing of all machines and equipment (how often)?; *Q11: What microbiological control do you apply (i.e. daily/weekly sampling, amount of samples of water, equipment, floor etc.)?; *Q12: What is the most challenging area with regards to Listeria control?

ited extent, is a carrier of *L. monocytogenes*, it will be impossible to prevent this pathogen from being introduced into processing plants. Focus should therefore be directed to sanitary measures and product conditions preventing growth. As reviewed by Rørvik [2], a significant risk factor is job rotation of the workers in the plant between different departments.

In order to eliminate *L. monocytogenes* from the processing environments, good production practices are needed, and the implication of Hazard Analysis and Critical Control Point (HACCP) programs [2, 9]. It is however pointed out, that the HACCP systems is the preferred strategy in most quality assurance programs, and it is recommended that microbiological criteria are only applied as guidelines in the verification of the HACCP system, and not for official control purposes [17].

Considering that seawater used in the tanks in the slaughterhouses was treated by UV, filtered and/or taken from depths ≥ 60 m (Table 4), the total aerobic count may be regarded as relatively high in the live chilling tank (Plant A and C only; Figure 5), especially when compared to the level on fish skin (Figure 4). The levels in bleeding and rinsing tanks are naturally higher than in live chilling tanks (Figure 5). Temperatures in all tanks are kept low to minimize growth of bacteria (Table 4). A comparison between the four different plants are not feasible because they were all sampled during full production, at different times in the day, and had different capacities. Also the fact that the prehistory of the fish is not known, as time since delousing, transportation time, and other factors influencing their internal and external microbiota composition and level, complicates a comparison.

4. Conclusions

- The pathogen bacterium *L. monocytogenes* was detected at three out of four visited slaughterhouses.

- *L. monocytogenes* was present in low concentrations, i. e., under the quantification limit of 100 cfu per L or m^2.

- *L. monocytogenes* was not detected on fish skin or gills, and it is not suspected that water tanks acts as reservoir for this pathogen.

- *L. monocytogenes* was detected in the gutting machines, and on conveyor belts, floors and drains downstream of gutting, implicating the gutting machine and the gutting area as hot spots for cross contamination.

- Detection of *Listeria* in machines and equipment, as in the present study from salmon slaughterhouses, represents a risk of contamination of salmon products, and the pathogen may be transferred to the final product meant for human consumption. Salmon products can thus not be ruled out as a potential source of listeriosis.

- It is important to stress, however, that it has never been documented that people have been infected by *L. monocytogenes* through consumption of Norwegian salmon products. Nonetheless, *Listeria* control is also important regards, public relations and to avoid recalls. In terms of food safety, the presence of *L. monocytogenes* represents a food safety risk by the present hygiene practices.

- Prevention of *Listeria* colonization in salmon slaughterhouses and processing plants is necessary in order to secure the production of safe food, and to maintain a good reputation for the industry. Since *L. monocytogenes* is a ubiquitous bacterium, it will be introduced from different sources. The design of processing machines and equipment minimizing colonization and with sufficient cleanability is therefore of utmost importance.

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