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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.

Keywords: Robotic cleaning; Fish processing; Serial manipulator; Listeria; Bacteria; Aquaculture Innovation

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 and shelf life of fresh fish (Gram & Huss, 1996; Trond 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

Table 1 Comparison of the manual and robotic cleaning time in minutes

Figure 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.

Busby 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 Figure 2; Figure 3 depicts typical installation locations for a future robotic cleaning system.

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 Figure 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 4K 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 Figure 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 Figure 6 and Figure 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 Figure 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.

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 Figure 9. For a more thorough explanation of the trajectory generator, we refer to Bjørlykhaug (2018).

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 Figure 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 dimensions of the mini fish slaughtering line cleaned in Experiment 2, as well as the sampling points for microbiological analysis are shown in Figure 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 Figure 11, with a bacterial suspension cocktail of *Pseudomonas fluorescens* MF05002 (Trond 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 (Figure 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_o) and after (N_x) cleaning, namely $\Delta N = \log N_x - \log N_o$.

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 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 Figure 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 Figure 14. The prototype in the test facility is shown in Figure 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 Figure 15 and Figure 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.

4.1 Microbiology

The decrease in the bacteria count in Experiments 1 and 2 can be seen in Figure 16. The decrease in bacteria after robotic cleaning in Experiment 1 (Figure 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 Figure 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 (Figure 16B).

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* (T. 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 60-70k 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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Table 1 Comparison of the manual and robotic cleaning time in minutes

Figure 1 The environment in which a robotic cleaning system will operate

Figure 2 Slaughtering line at facility 1

Figure 3 Slaughtering line at facility 2

Figure 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

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

Figure 6 Robotic system 2 in the test facility

Figure 7 Kinematic chain of the custom robot in prototype 2

Figure 8 Nozzle arrangement

Figure 9 Overview of the control system

Figure 10 Prototype 1 during Experiment 1

Figure 11 Spraying of the inoculation mixture in Experiment 2

Figure 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)

Figure 13 Manual cleaning in Experiment 2

Figure 14 Simulation of the cleaning process

Figure 15 Prototype 2 spraying water

Figure 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 Figure 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}*)*

Figure 17 Prototype 2 spraying soap

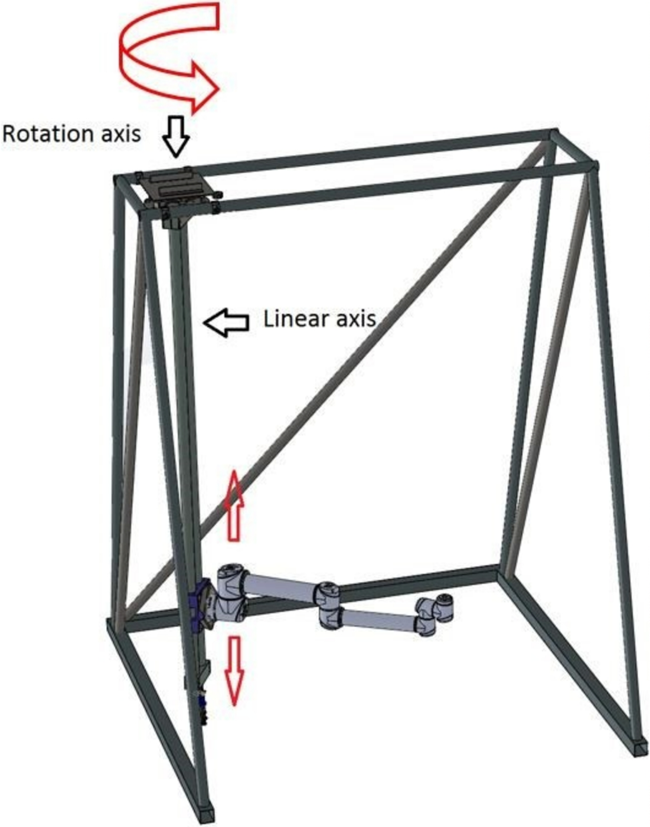
Highlights: Experimental study of effectiveness of robotic cleaning for fish processing plants

The cleaning of fish processing plants is in large part a costly operation which is unstable in terms of outcome.

Two cleaning experiments in which a robot is used to do cleaning of bacteria inoculated fish processing equipment is done.

Both experiments show very promising results after testing, indicating that robots could clean fish processing plants.

Robotic cleaning of fish processing plants could enable more stable cleaning results and mitigate bacterial contamination.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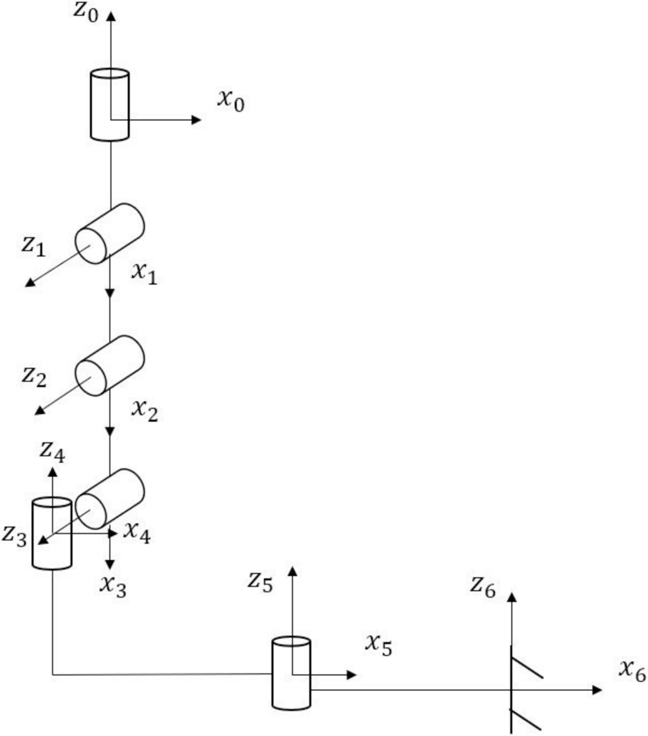
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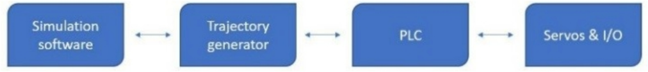
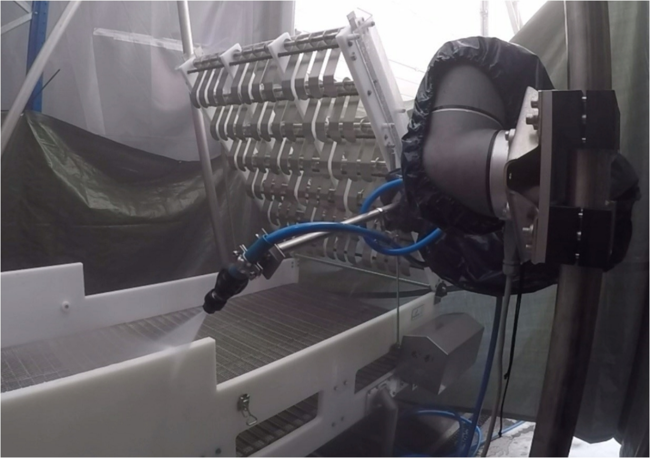
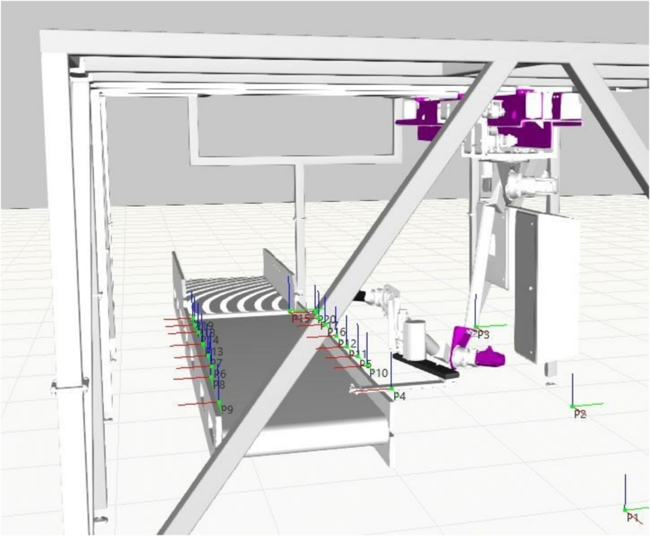

Simulation software
Trajectory generator
PLC
Servos & I/O




S1
P2
P1
S2
00mm
P4
S4
P3
5750mm
S3
1030mm
1000mm


P15
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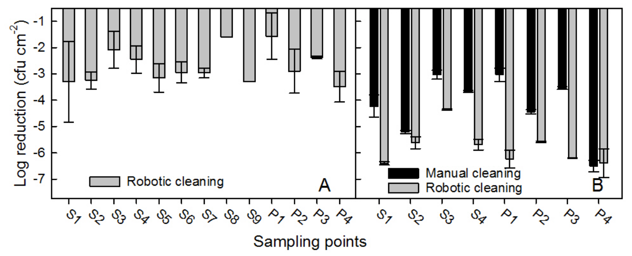
Log reduction (cfu cm^{-2})
-1
-2
-3
-4
-5
-6
-7
Robotic cleaning
A
S1
S2
S3
S4
S5
S6
S7
S8
S9
P1
P2
P3
P4
Manual cleaning
Robotic cleaning
B
S1
S2
S3
S4
P1
P2
P3
P4
Sampling points

Table 1 Comparison of 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*
Robotic time	33	33	33	33	33	185*

**Included in the total time is 2 x 10 minutes of waiting time between applying foam and rinsing to allow the chemicals to work*