Development and Validation of Robotic Cleaning System for Fish Processing Plants

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***Abstract*—This paper presents the development of a robotic cleaning solution for a fish processing plant. The project is currently at the stage of a first prototype consisting of a serial manipulator, a vertical linear axis and a rotational axis for the vertical axis. The purpose of the prototype is to validate the cleaning quality of a robotic cleaning solution. A cleaning solution will have to spray the equipment and machines in the processing plant with chemicals and water to remove fish residue and bacteria, and special design considerations have to be taken with regards to water proofing and corrosion resistance. In order to validate such a system, a cleaning test was performed on an electric stunner, a machine typically found in salmon slaughterhouses. Results from the cleaning test show that robotic cleaning of fish processing equipment gives promising results. However, several issues related to making a system that can clean a whole plant are not resolved. Further work will require the development of a custom serial manipulator and a custom linear axis for navigating the manipulator.**

The main purpose of this paper is to present design considerations and investigate the validity of a robotic cleaning solution aimed at fish processing plants. This research is at TRL 5, with validation of technology in relevant environment.

I. Introduction

The fishing industry is a multibillion dollar industry in Norway with a yearly revenue of over 40 billion NOK for salmon alone [1]. The salmon industry faces critical challenges that may limit further growth. In particular an ever increasing amount of lice *(Lepeophtheirus salmonis)* and the constant danger of *Listeria monocytogenes* contamination during production has lead to stricter requirements from the government each year. On background of this, the industry has to find new ways of improving their procedures for breeding and slaughtering, including improved cleaning procedures to reduce the risk of bacteria outbreak.

To cope with the risk of *Listeria monocytogenes* and other bacterial contamination, processing plants must be thoroughly and frequently cleaned [2], and in the case for salmon processing plants, they are cleaned every day. This is done by cleaning crews at night after the production has been shut down. This costs millions in labor every year for a processing plant. In addition, there are high expenses related to chemicals and water. Moreover, the chemicals produce a toxic cloud inside the processing plants during cleaning, which introduce health hazards for the cleaning personnel. A robotic cleaning system could reduce cost, both from labor, and also from potentially reducing the amount of chemicals and water used during cleaning. It could also improve the HSE for the workers by reducing their exposure to the hazardous cleaning environment.

Robotic cleaning systems are already well established in the literature. However, most robotic cleaning systems are aimed at cleaning of flat surfaces, e.g. floors, walls, windows [3] and solar panels [4]. The cleaning systems may have large working areas, but they are limited to moving in two dimensions, usually not operating in 3D space. However, there are exceptions. Cleaning systems such as hull cleaning [5] and car/truck washers [6] can operate in three dimensions and clean objects of arbitrary shape. Cleaning is similar to spray painting [7] [8], and it may be possible to use techniques and technologies from that field and apply them to the field of robotic cleaning of fish processing plants.

To the best of the authors' knowledge, there are no cleaning solutions in the literature that has to navigate fairly large spaces in three dimensions (10m x 10m x 10m) with many obstacles in its path, while providing centimeter accuracy. The closest solutions, albeit not for cleaning, are long reach robots intended for nuclear inspection [9] [10]. These manipulators have long reaches (>5m), while having low weight (<100kg). Other types of long reach manipulators in the literature are manipulators intended for operation in space. The big advantage of operation in space is the absence of gravity, resulting in lower torques on joints [11].

Therefore we present in this paper a new robotic cleaning system. The cleaning system is a long reach manipulator constructed using standard industrial components. The concept of mounting a robot to a linear axis is nothing new, but the application is new. We also present design considerations that needs to be taken for a robotic cleaning system intended for fish processing plants. Lastly, we present a cleaning experiment which was carried out in order to evaluate whether robotic cleaning of fish processing equipment can provide satisfactory hygiene.

II. Requirements of a Robotic Cleaning System for Fish Processing Plants

Several challenges arise when comparing making components and equipment for salmon processing plants versus conventional industry or even regular food industry. The environment is wet and humid, and has to be thoroughly washed with corrosive chemicals each day to keep bacterial growth away. In addition, mechanical components has to use oil approved by the food industry due to the danger of contamination of the product. The materials used to build the components also have to be approved, common materials are nylon and stainless steel. Aluminium and regular steel are not recommended due to corrosion and surface roughness [12], even with surface treatment such as paint. Low surface roughness is highly recommended as it results in easier cleaning and less adhesive biofilm. This is part of the ”design for cleaning”. Another aspect of the ”design for cleaning” is to avoid using bolted connections, closed profiles (e.g. round and square pipes), tight gaps, large contact areas between parts that are bolted and other areas where water can get trapped. In addition, it is important to have an ”open” design, meaning that it is easy to clean every part of the machine. It is highly unwanted to introduce new sources for bacterial growth, so a new cleaning solution should adhere to the aforementioned ”design for cleaning” practices, and in addition the solution should move away from the processing area and be cleaned and dried after the cleaning of the factory has been completed.

The workplace is a crowded area, with already a lot of equipment placed on the floor. Many of the processing plants where a possible robot cleaning solution could be implemented are already built, resulting in the possibility of making space for the cleaning solution very limited. At the most, one new factory is built each year in Norway. Rather than building new factories, the old factories are replacing their old machines. The floor is not only crowded, but usually have a lot of different height levels, rendering a robot based on wheels highly impractical. Fig. 1 shows the problem with different height levels and crowded workplace. A possible solution would thus be to hang the robot from the ceiling.

Many challenges arise when mounting a robot underneath the ceiling in a salmon processing plant. Some of the processing plants are based in old, wooden buildings with a limited load carrying capacity of the ceiling. This will limit the weight of the robot, and thus the reach of it. But for the cleaning solution to be a useful solution, the reach will have to be long enough to clean more than one machine. A horizontal transportation system for the robot will help in this regard. Unfortunately, the components in a processing plant is not placed in a straight line, and the horizontal transportation system will need to move the robot in more than one axis, either with two parallel axes, or by a linear axis with curvature. The problem with the two parallel axes is the space needed to implement it. If the processing plant has not yet been built, the parallel axes can be taken into consideration in the drawing board, making such a solution possible. However, that is rarely the case. The linear axis with curvature in thus the only possible solution. The problem with that solution is that there is no linear axis with curvature on the market that has propulsion which is corrosion resistant. A magnetic propulsion system is ruled out due to the corrosive environment. In addition to all these challenges, cables and hoses usually hang down from the ceiling, making the navigation complex. There is also the matter with rules and regulations related to hanging heavy objects from the ceiling.

The workers operating the processing plant does not have any programming experience, and the robot cleaning system will therefore need to be simple to operate, preferably just by the push of a button. This implies that the robot will have to be able to perform its task with no manual adjustment in case some of the equipment is moved. This could result in the need for a computer vision system to adjust the robot paths to make the system user friendly enough.

The requirements can be summarized as follows:

- Low installation time.
- Little change of existing processing plant infrastructure.
- Must ensure satisfactory hygiene.
- Reach of installation.
- Dexterity over the working area.
- Sufficient stiffness in the suspension if scrubbing is necessary.
- Avoidance of intrinsic contamination.
- Easy to use.
- Safety.
- Price.

Low installation time: Due to constant activity at the slaughterhouses all year around, the installation time needs to be kept at a minimum in order to stop production. The slaughterhouses usually have stops for 2 weeks in the summer, but the best solution would be able to build the robot cell just in the course of a weekend.

Little change of existing processing plant infrastructure: Changing the existing processing plant infrastructure can result in a lot of extra work when installing, and can also reduce the efficiency of the plant. The plants do often have equipment and machines placed on elevated levels and floors, meaning that not just the machines will have to be removed, the elevated floors will also have to be reworked.

Must ensure satisfactory hygiene: The main objective of the cleaning process is to eliminate the risk of microbial contamination of the processed food. The purpose of the robot would be diminished if e.g. *Listeria monocytogenes* could contaminate the salmon. Special design consideration would have to be taken to minimize the risk.

Reach of installation: In order for the robotic cleaning solution to be a economical viable solution, it has to cover a lot of area. If the area the robotic solution is able to clean is small, the cost and inconvenience is not worth it. The reach of the solution is thus of very high importance.

Dexterity over the working area: This point is related to the one above, but it is just not the area that is important. Some parts of the equipment needs to washed from the side and the underside.

Sufficient stiffness in the suspension if scrubbing is necessary: Experience from the slaughterhouses have shown that certain parts of the equipment are more susceptible of growing though films that will not come off just from washing, and scrubbing is necessary. However, there is some uncertainty whether this is due to inadequate regular cleaning which allows the films to grow. If scrubbing is necessary, the complexity of the solution will increase drastically.

Avoidance of intrinsic contamination: Since salmon is food, precaution have to be taken in order to avoid contamination with elements for the cleaning system itself, i.e. oil, chemicals, metal debris etc.

Easy to use: The people operating the processing plants are not robot experts and automation engineers, thus the robot will have to be easy to use. Preferably just a start and stop button.

Safety: Safety is of course a main concern when working with robots. The idea is that a final robotic cleaning system will replace the cleaning crews which operate at night, and that the system will operate without any assistance from human operators. That way, the whole processing plant can be cleared for people at night before the robots starts cleaning. Sensors on doors can be used to ensure that no personnel enter while it is working, thereby ensuring safety.

Price: Price is of course an important aspect. Even though a lot of money is spent on labour related to cleaning, the price has to be kept down. This is related to the uncertainty of how well the solution will work, or if it will break down within a short time frame.

III. PROTOTYPE

The prototype was built with the purpose of being able to clean one electric stunner. If a stationary robot was to be used it would have to have a reach of minimum 2 meters in order to be able to clean the whole machine. Even though this prototype's main purpose was just to test the cleaning quality of a robotic cleaning solution, a robotic solution resembling what the final product possibly will look like was preferred. The prototype thus consisted of a UR10 6DOF robot mounted on a vertical linear axis. The vertical linear axis has a stroke of 2500 mm and is operated by spindle drive. The vertical linear axis is then mounted to a slewing ring in order to expand the working envelope of the assembly. For the purpose of this experiment, a support frame was built. In a finalized version of the cleaning robot, the robot will hang from the ceiling, possibly with a rail system in order to increase the working space of the cleaning system. The assembly of linear axis and rotation axis can be seen in Figure 4. A final step to increase the working envelope of the prototype was to install the spraying nozzle on a lance mounted on the end effector. The complete prototype can be seen in Figure 5.

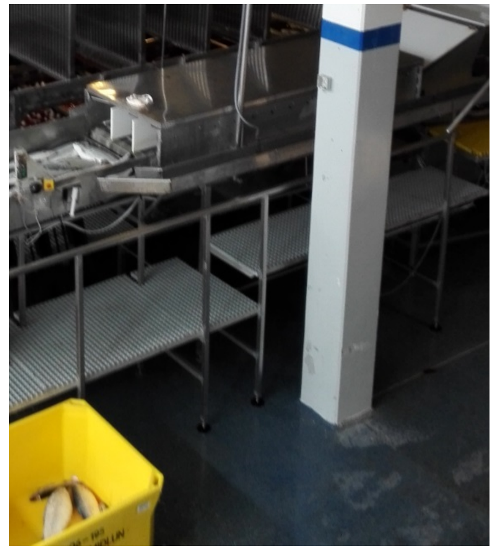

Fig. 1. Some of the challenges in a salmon processing plant. Notice the different height levels between the floor and the walkway, the narrowness of the walkway and the cables hanging from the roof down to the machine.

Fig. 2. The difficulties related to hoses, cables and pipes coming down from the ceiling further emphasised.

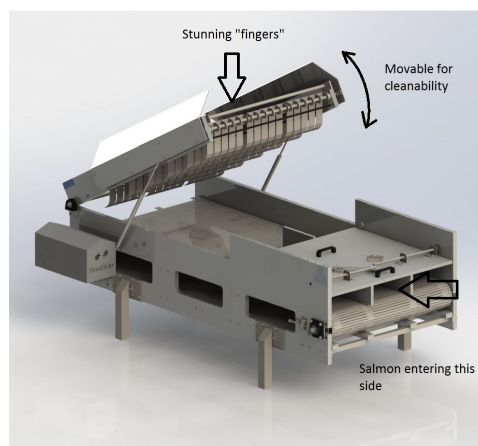

Fig. 3. A CAD drawing of an electric stunner, a typical machine in a fish processing plant. The electric stunner is shown in the cleaning position, with the array of stunning fingers tilted up.

The main control system for the cleaning solution is a OMRON PLC with a EtherCAT interface to control the servos on the linear axis and the slewing ring. The servos are OMRON R88M series with gearing 50:1 and 10:1 for the slewing ring and linear axis, respectively. Modbus is then used to

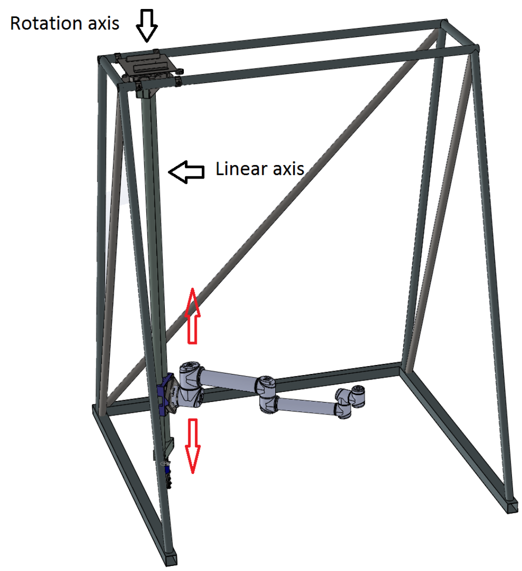

Fig. 4. A CAD model of the linear axis and rotational axis assembly. A support frame was made to be able to suspend the assembly from the "ceiling".

Fig. 5. The finished prototype. The lance and the spraying nozzle is not mounted.

communicate between the PLC and the UR control system, see Figure 6. Flags are used to tell the PLC to move the axes, and the PLC returns True when a movement in complete. The UR control system acts as the Master, while the PLC is a slave. A compressor and mixing station was used to supply foam and water to the nozzle.

A. *Drawbacks of the prototype*

One of the main drawbacks of the prototype was the interaction between the axes controlled by the PLC and the robot. Since they did not share a common control system which integrated the kinematics for both, they had to move independently. The world coordinate system of the robot was not connected to the position of the linear axis and the rotation axis, which resulted in a world coordinate system which changed its correspondences with the real world every time the robot base was moved, complicating programming of the robot trajectories.

Due to the length and weight of the linear axis with the mounted robot, resonance of the assembly was an issue. To compensate for this, the robot had to move with reduced acceleration.

Another drawback with the prototype was the UR10. This robot is made from aluminium, have low IP grade and is thus not suited for the intended environment. A protective coat was used during the cleaning experiment, but this is just a temporary fix not suited for industrial use as the robot will not be hermetically sealed and the corrosive chemicals will probably still enter the robot and cause damage.

IV. Cleaning experiment

A cleaning experiment with the prototype was performed in cooperation with Nofima AS - Norwegian Institute of Food, Fisheries and Aquaculture Research.

A. *Method*

An electric stunner was inoculated with a bacterial suspension cocktail of *Pseudomonas fluorescens* MF05002 [13], *Pseudomonas putida* ATCC 49128 from the American Type Culture Collection, and *Photobacterium phosphoreum* CCUG 16288 from the Culture Collection University of Gothenburg. All bacteria were initially grown separately to stationary phase at 30°C and 150 rpm in a shaking incubator in Tryptic Soy Broth with 0.6% Yeast Extract (TSBYE; Oxoid) before they were pooled together, stored at 4°C and used within 24 hours. The electrical stunning machine was inoculated by spraying with a household spray flask on all open surfaces. Spraying was repeated once each hour 5 times. After 24 h of the first spraying, an incomplete biofilm had developed on the surfaces (Approx. 10^5 cells cm^{-2}). Prior to washing, 15 predefined control points were swabbed (25 cm^2) with Floq Swabs (Copan, Italy) that were then placed in a 10 mL volume consisting of 9 mL buffered peptone water (Oxoid) and 1 mL inactivator [14]. After the washing procedure was finished, and the stunning machine had air dried, another 15 predefined control points were either swabbed (25 cm^2) or sampled by the use of Sodibox cloths (Sodibox, La Fort-Fouesnant, France) to achieve a larger sampling area (300 - 2000 cm^2). Some of the control points can be seen in Figure 8. The samples were kept on 4°C until plating within 24 h. The bacteria present on the swabs were resuspended by shaking (250 rpm) at room temperature for 30 minutes. Sodibox cloths were suspended in 100 mL buffered peptone water (Oxoid) and subject to homogenization using a stomacher machine (Seward) for 2 minutes. Serial dilutions of the samples were spread plated on Tryptic Soy Agar with 0.6% yeast extract (TSAYE; Oxoid) and

Fig. 6. The hardware architecture and its interfaces.

Fig. 7. The prototype during the cleaning experiment.

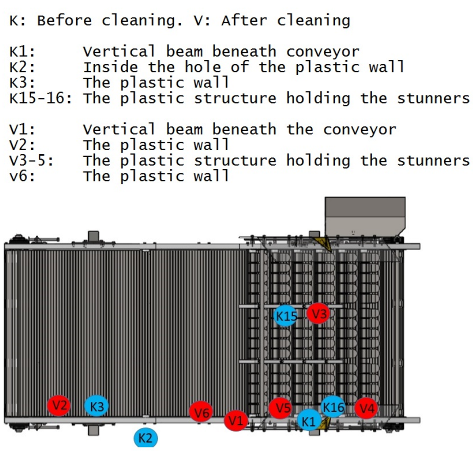

Fig. 8. Some of the control points during the cleaning test. Electric stunner seen from above. Blue dots are control points before cleaning and red dots are after cleaning. Certain parts are more difficult to clean than others, such as the plastic sliding surface for the conveyor belt.

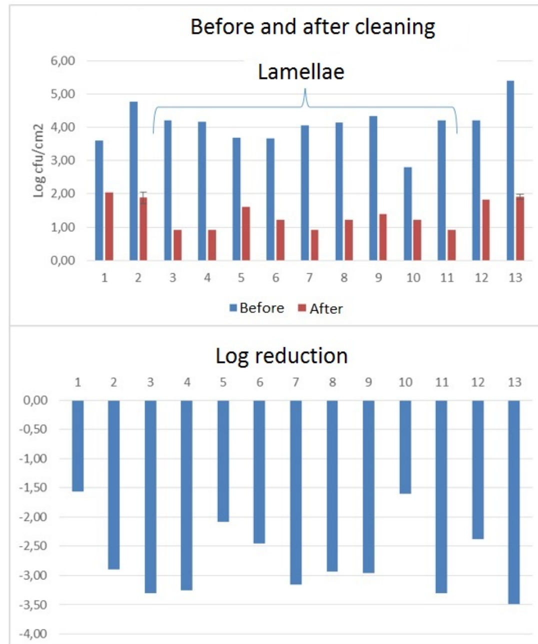

Fig. 9. Results from the cleaning test. In the top graph the bacteria count is shown before (blue) and after (red) cleaning,. The different control points are marked 1 to 13. The bottom graph shows the decrease in bacteria count before and after cleaning.

incubated at 30°C for 48 h before the bacterial concentrations was calculated as colony forming units (cfu) per cm^2.

The robot was programmed manually to spray all surfaces of the electric stunner in a zig-zag pattern, both from above and from underneath. The nozzle distance was approximately 20 cm. First, the electric stunner was sprayed with a soap foam, then it was sprayed with clean water to rinse it. The chemicals used to make the soap foam, provided by Lilleborg, is a type commonly used for cleaning in fish processing plants.

B. Result

The results from the cleaning test can be seen in Figure 9. The decrease in bacteria after cleaning was promising, and for some of the control points the bacteria count was close to the detection limit (0.5 - 1 log cfu/cm^2) after the cleaning. While this test only focused on bacterial removal, it is safe to assume the removal of fish residue is sufficient since workers at the end of their shift always do a rough flushing of equipment with clean water. This is to remove fish residue and blood before it starts sticking, which it will do if it starts drying.

V. Conclusion and Further Work

It can be concluded that a robotic cleaning system can deliver sufficient cleaning quality for fish processing plants.

Further work will revolve around building a slender, long reach manipulator suitable for fish processing plant environments. A curved linear axis/rail system suited for ceiling mounting for transporting the manipulator will also have to be developed. Building a custom manipulator will result in the need for a control system. Building the control system from the bottom up will open up the possibility for integration of motion for the manipulator and linear axis/rail system, giving a complete kinematic model, where motion of the linear axis will result in changes for the world coordinates for the manipulator. Hopefully this will overcome all the drawbacks of the current prototype.

The programming of the robot motions for the washing experiment was cumbersome. Further work will require the possibility for performing offline programming and simulation of the robotic cleaning, and transferring that directly to the robot. This will also help with collision avoidance.

Further work should also investigate the usage of computer vision in order to improve the accuracy of the robot movements.

ACKNOWLEDGMENT

The authors would like to thank Optimar AS, NTNU in Aalesund, Nofima and Lilleborg. This research was funded by the Research Council of Norway, grant no. 245613/O30

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