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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.

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

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	$7 \times 5 \times 3$ m = 105 m^3
Scans	6
Time to scan	Approximately 1 h
Scan data size	Approximately 900 mb

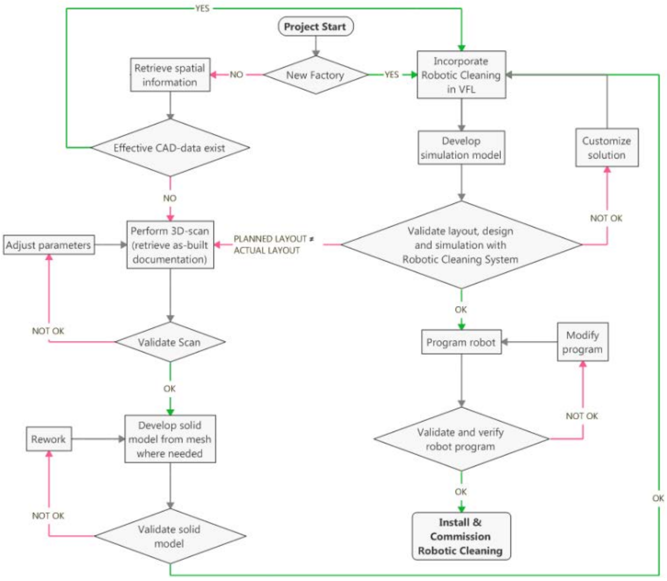

Fig. 5 Workflow for implementing robotic cleaning solution

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.

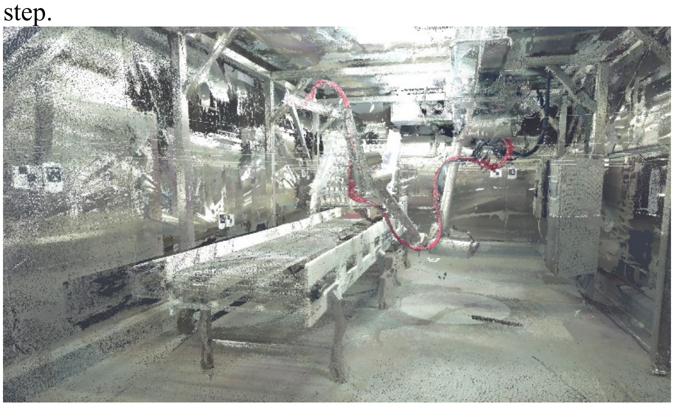

Fig. 6 Point cloud of scanned lab in Autodesk ReCap

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

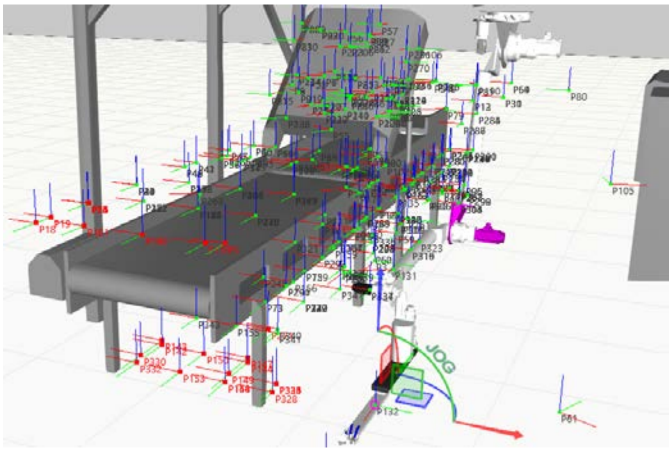

Fig. 8 Solid model from mesh used for simulation in VC

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.

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