SINGULAR SIMULATION OF REAL FISH IN FISH PROCESSING FACTORIES

Paul Steffen Kleppe, Lars Andre Giske, Ola Jon Mork and Irina-Emily Hansen
Department of Ocean Operations and Civil Engineering
Norwegian University of Science and Technology
Larsgardsveien 9, 6009 Aalesund, Norway
paul.s.kleppe@ntnu.no

KEYWORDS

Fish; Simulation; 3D-Modelling; Virtual Fish

ABSTRACT

Much effort is put into researching the simulation of manufacturing systems and operations, typically Discrete Event Simulation for systems and machining simulations. These simulations are often limited to idealistic behavior within the systems (e.g., no physics involved) and infinitely rigid objects (e.g., no bending or other impacts from tools). This research presents a development of a simulator for soft bodies within a physics engine; the case studied is the effects of physics on fish within a production system. The developed simulator was benchmarked against a physical production system through a quantitative experiment, and the solution shows promising results in mimicking the behavior of fish within a production system. The research also suggests that data must be mapped to create an accurate digital representation of a fish.

INTRODUCTION

This paper presents a simulation study in which a novel developed digital fish model is proposed to aid in the testing of Fish Processing Equipment (FPE) in fish processing plants (FPPs). The study was conducted in the Norwegian aquaculture industry (NAI).

The high throughput of fish in current FPPs is challenging for installing and commissioning complex equipment/retrofit. Furthermore, most plants run two processing shifts five days a week throughout the year. These factors make the allotted time window for installation and commissioning very short. Violating the allotted installation time due to errors during planning has a significant cost impact, with fish prices exceeding 5 USD per kg [1]. In addition, doing such retrofitting into existing FPPs is accompanied by an increased risk of bacterial contamination [2], [3] and [4] and the threat increases with installation time. These factors create a need for an efficient method to reduce commissioning costs and time. NTNU Aalesund has dedicated work to developing concurrent engineering tools and digital twin and virtual models through Manulab for manufacturing excellence, Industry 4.0 and Engineering Education 4.0 [5], and their collaboration with the Biomechanical lab at Aalesund General Hospital. As part of the collaboration, the team developed 3D-Scanning technology for organic surfaces [6], [7] to enable rapid scanning of objects. Further, the collaboration effort also developed robotic testing of material properties and rigidity in human joint flesh [8], and methods for quick setup for testing many samples [5]. The technology roadmap in figure 1 shows interaction and technology development in collaboration with Manulab and the Biomechanical lab, which may also be used as a roadmap for achieving realistic virtual fish.

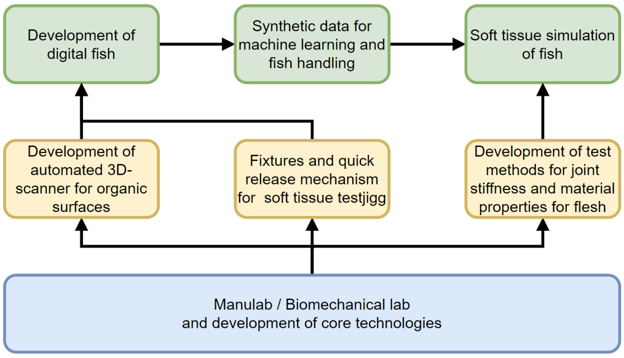

Fig. 1: Technology roadmap for the development of realistic digital fish

This research utilizes these experiences to explore the first steps for creating digital fish and virtually testing FPE in a simulator to reduce flaws and shorten the time to the market.

Theory - Simulation

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 [9] to evaluate and predict the real-world system's behavior. For a while, DES models have been standard as 2D visualizations; however, as CAD capabilities have grown, DES visualizations in 3D have

Communications of the ECMS, Volume 37, Issue 1,
Proceedings, ©ECMS Enrico Vicario, Romeo Bandinelli,
Virginia Fani, Michele Mastroianni (Editors) 2023
ISBN: 978-3-937436-80-7/978-3-937436-79-1 (CD) ISSN 2522-2414

become more common [10], [11]. In addition, DES visualization models are essential for validation and verification processes, aiding the communication of results and attaining a shared understanding of both models and results [9], [10], [11] [12].

Numerous methodologies for carrying out DES studies have been developed [9], [13]; however, all of them include a combination or derivative of the steps proposed by Musselman [14]: 1) Problem formulation, 2) Model conceptualization, 3) Data collection, 4) Model building, 5) Verification and Validation, 6) Analysis, 7) Documentation and 8) Implementation. A few of these steps may be omitted, a few could overlap, and a few could be iterated. Overlap can occur when data collection continues during model construction owing to time constraints, or iterations may occur if the analysis fails to satisfy the requirements of the problem formulation [9].

Furthermore, DES studies often imply the idealistic behavior of the parts in the simulation. However, for developing FPE, the fish cannot behave as an ideal rigid object within the developed equipment, as the fish has a soft body with variations in size and weight. There is, therefore, a need to account for the behavior of the soft body within the simulation environment when simulating the performance of FPE. In this research, the researchers have still chosen to use the DES model steps to structure the study, as the researchers did not find any other adequate models.

METHOD

For this study, steps 1 to 5 in the DES framework have been applied. 1) Model Conceptualization, 2) Data Collection, 3) Model Building, 4) Verification and Validation. Steps 6 through 8, Analysis, Documentation and Implementation, were not used in this research.

Problem Formulation

The underlying need is to be able to test machines for fish processing without involving real fish. Solving this need reduces development time and costs, as mentioned in the section on Simulation Theory. The problem is that there are no virtual models of fish with fish behavior as part of the model, and all other fish simulations only consider fish as ideal rigid bodies without gravity affecting them.

Model Conceptualization

The research team started by building a fish model like a rag-doll [15]. The fish model consisted of five rigid bodies connected with joints from an open-source unity model. The hypothesis behind this choice of model was that the fish would have different rigidity and weight distribution along the length of the fish, and this type of model would consider those differences.

The following data has to be collected to create a virtual fish: 1) Weight and weight distribution. 2) Degrees of freedom (DOFs), deflection limit, and rigidity for each joint. 3) Texture mapping.

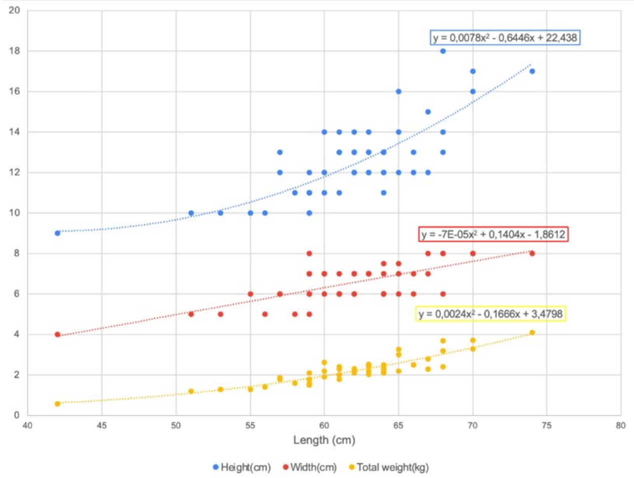

Fig. 2: Relationship between length, height, width, and weight of the fish

Data Collection

The researchers gathered data from many farmed salmon specimens to make this digital model more like a real fish. Height, width, length, weight, and weight distribution were measured for several fish. An example of the logging setup is seen in Fig. 3. The fish data set consisted of 49 farmed Atlantic Salmon (*Salmo salar*). The data were normally distributed and put into a virtual fish model. The length of the fish constituted the base as it was deemed to be the variable that changed the overall shape of the fish to the greatest extent. Polynomial regression mapped all other values to the length (Fig 2). The following steps were taken to capture the data: 1) Measure stiffness before rigor, which here was measuring how much the fish would bend; 2) Measure dimensions, length, height and width, and total weight; 3) Picture for texture mapping; 4) 3D-scanning; 5) Cutting and dividing each fish sample into pieces to measure weight distribution.

Model Building

The Unity model is based on a 3D model with a simulated skeleton and a simple collision system. The model built in Unity is relatively simple, but it works as a good analog and a simple proof of concept model for the dynamics of a dead fish. Functions were written to generate a normally distributed length, and other values were calculated. The relationship between each length and each parameter was calculated in Python using polynomial regression (as seen on the graph) and then implemented in the Unity script in C#.

The salmon model had its skeletal structure modeled in Blender [16]. Next, the visual models were imported into Unity 3D and rigged with" Capsule Colliders" and" Rigid Bodies" for physical simulation, as seen in Fig 7. These components add an interactable shape to the object, which enables the computer to calculate physics and collisions. Finally, the skeleton was rigged with "Character Joints" to simulate realistic skeletal

Fig. 3: Logging setup for Atlantic Salmon (Salmo Salar)

Fig. 4: Measuring stiffness for fish

movement. The character joints pivot around their connected joint and constrain their movement. Angle constraints for the joints were extrapolated from photos of bent fish, as seen in Fig. 4. During the development of the models, no actual data was used, and testing was done iteratively by eye until it "looked right" from the researchers' perspective. After creating a model baseline, the collected data was used as input.

Verification and Validation

The simulation model was exported to WebGL [17] through the built-in support in Unity to facilitate user-friendly testing and evaluation of the simulation model in a web-browser environment, which consists of conveyors moving fish. The development mainly consisted

Fig. 5: Parting fish for measuring weight distribution

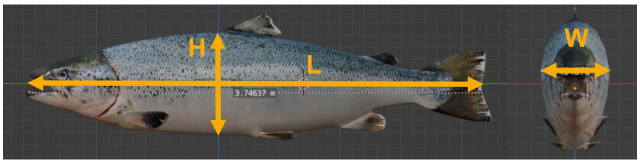

Fig. 6: Measured diemnsions - Length (L), height (H) and width (W)

of watching a captured video of fish behavior and modifying values within Unity. For example, when spawning a fish in the simulation model, a normally distributed random value is selected for the size, and weight and other values are mapped accordingly to each size value.

The simulation software was then used to predict fish behavior within the conveyor system, and the behavior was tested with live fish, Atlantic salmon, for comparison afterward. Finally, the same conveyor system used in the virtual environment of Unity3D was built and tested with fish to validate the digital fish behavior. The version used throughout was Unity 2021.3.9f1.

RESULTS

The results are represented through the final parameters which are used for the digital fish, which performed well against a physical test for comparison. That test setup is also presented, along with a qualitative evaluation of it.

Data Collection

The rigidity is measured alongside its length and weight to map the fish. The fish was then partitioned to measure the weight of each part of the fish. Example values from one fish (sample #16) in table II. Species salmon. Length 68 cm, Height 18 cm and width 8 cm, measured as seen in Fig. 6.

Sample	Length	Height	Width	Weight
#14	65 cm	16 cm	7 cm	3,271 kg
#15	42 cm	9 cm	4 cm	0,570 kg
#16	68 cm	18 cm	8 cm	3,698 kg
#17	61 cm	14 cm	7 cm	2,406 kg
#18	57 cm	13 cm	6 cm	1,866 kg
#19	63 cm	14 cm	7 cm	2,525 kg
#20	62 cm	14 cm	7 cm	2,321 kg

TABLE I: Measured values for sample #14 to #20 Atlantic Salmon (Salmo Salar)

Body	Name	Weight	Distribution
Body 1	Head	0,492 kg	13,3 %
Body 2	Upper body	1,277 kg	34,5 %
Body 3	Lower body	1,085 kg	29,3 %
Body 4	Tail	0,761 kg	20,6 %
Body 5	Back fin	0,083 kg	2,2 %
Total		3,698 kg	100,0 %

TABLE II: Weight values and distribution for body parts for sample #16

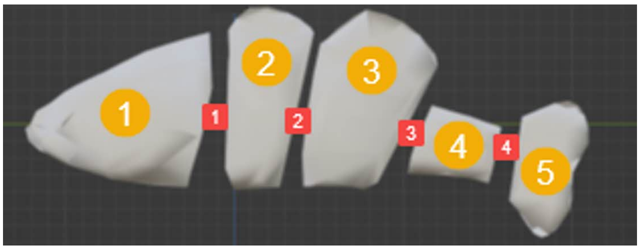

Fig. 7: Five rigid bodies and four rigid joints defined

Model Parameters

The Unity model was built as described in the section on Model Building.

Rigid bodies and rigid joints with movement limits approximate the fish's behavior. Angular drag Fig. 10 has been added to achieve satisfying behavior and simulate tissue/flesh around joints and rigid bodies. Joints have the parameters as shown in Fig. 11 which is a customized joint for the fish. The parameters are indicated around the joints' local coordinate system which are aligned with the global coordinate system as seen in Fig. 9. The joints are of the type "character joints" which are used for rag-doll effects and they are extended ball-socket joints that allow you to limit the joint on each axis as seen for one specific joint in Fig. 12. In Table III the different values for each joint are shown.

Each bone structure is modeled as a rigid body with joints connecting them. They control a set part of the model based on the weight distribution data described in table II. For example, for the figures below, the head is selected, and it will control everything not blue in Fig. 8. There is, however, a gradient, indicating that the parts colored green are also affected by what is happening to the bone representing the head (i.e., the bones are linked). The models were then used to test what configuration looked most realistic and added constraints. Further, the fish were collided into the ground in Unity to iterate toward a natural behavior of the fish model. Fig. 11 shows a snapshot of the values of a specific random generated fish at a point in time.

Lastly, for the virtual model, a picture of a salmon was scaled and mapped directly onto the unity model to create a more realistic visual representation.

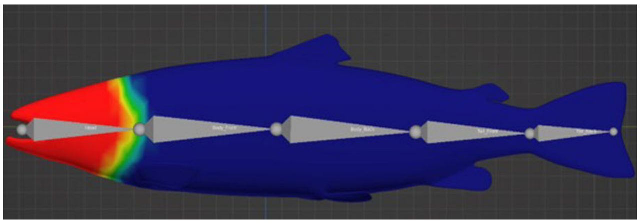

Fig. 8: Five rigid bodies and four rigid joints defined

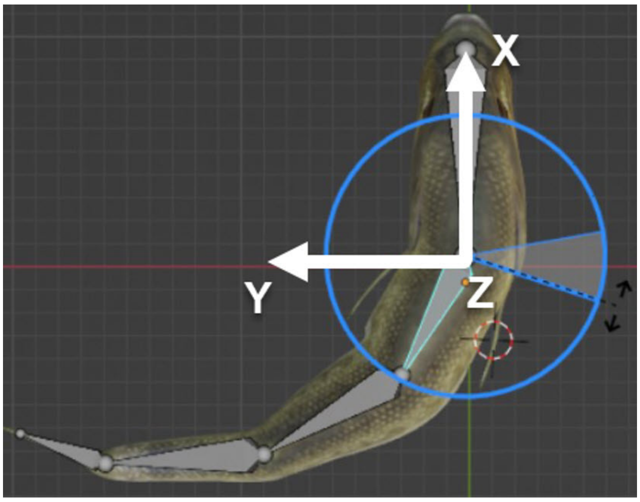

Fig. 9: Joint 1 between rigid body 1 and rigid body 2

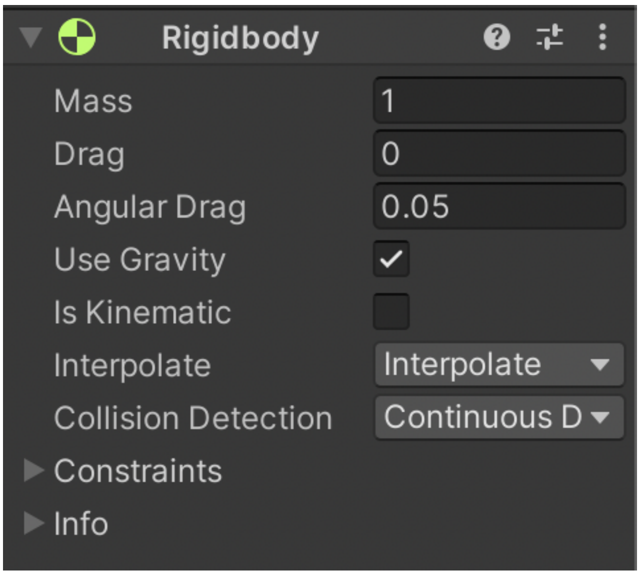

Fig. 10: Rigidbody parameters

Characteristics	Joint 1	Joint 2	Joint 3	Joint 4	Comments
Connected bodies	1 and 2	2 and 3	3 and 4	4 and 5	Bodies connected to each individual joint
Twist Limit Spring	[0, 0]	[0, 0]	[0, 0]	[0, 0]	Spring force to bring back the joint if going past the limit position in twist axis [spring, damper]
Low Twist Limit	[0, 0, 0]	[0, 0, 0]	[0, 0, 0]	[-22.5, 0, 0]	The lower limit of the joint [limit, bounciness, contact distance]
High Twist Limit	[0, 0, 0]	[0, 0, 0]	[0, 0, 0]	[22.5, 0, 0]	The higher limit of the the joint [limit, bounciness, contact distance]
Swing Limit Spring	[0, 0]	[0, 0]	[0, 0]	[0, 0]	Spring force to bring back the joint if going past the limit position in swing axis [spring, damper]
Swing Limit 1	[13.75, 0, 0]	[13.75, 0, 0]	[30.5, 0, 0]	[21.5, 0, 0]	Limits the rotation around the swing axis [limit, bounciness, contact distance]
Swing Limit 2	[3.5, 0, 0]	[3.5, 0, 0]	[13.5, 0, 0]	[15, 0, 0]	The axis orthogonal to the two other axes [limit, bounciness, contact distance]

TABLE III: Joint Characteristics from Unity Model

Fig. 11: Features defining the body components

Physical Test Comparison

The table only shows one run of the simulation vs. one test set-up on the shop floor with real fish. In the simulation, the conveyor speeds were not significant. The mutual behavior between the fish and between the fish and the conveyor system were the most important parameters to study. Therefore, the capacity of the simulated system is much higher than what is achievable in the real world due to the unrealistic speeds of the conveyors in the system. Table IV therefore shows a high capacity, but the rate of singulation was the driving parameter. In reality, there are other bottlenecks of approximately 30 fish per minute (FPM) which limits the capacity.

Parameters	Real	Simulation
Number of fish in system	18	23
Time for throughput	45 s	8 s
Fish per minute in	24	173
Singulated fish	10	12
Singulation rate	56 %	52 %
Fish per minute out	13	90

TABLE IV: Comparison of performance between virtual and physical test

The industrial board of six fish industry experts compared the virtual and physical settings. Eighteen fish were dropped at the left end of the system, and conveyor belts with increasing speed moved the bulk of fish to the right. The observations showed that the speed changes caused the fish bulk to be stretched identically in both the virtual and physical models (figures below). The actual fish movements and distribution on the physical conveyor were like the digital fish in the simulation environment, albeit not with the same accuracy. The similarity applied to fish-to-fish and fish-to-conveyor interaction, and the interaction was accepted as an initial approach that shows promise but needs further refinements to be used as a tool.

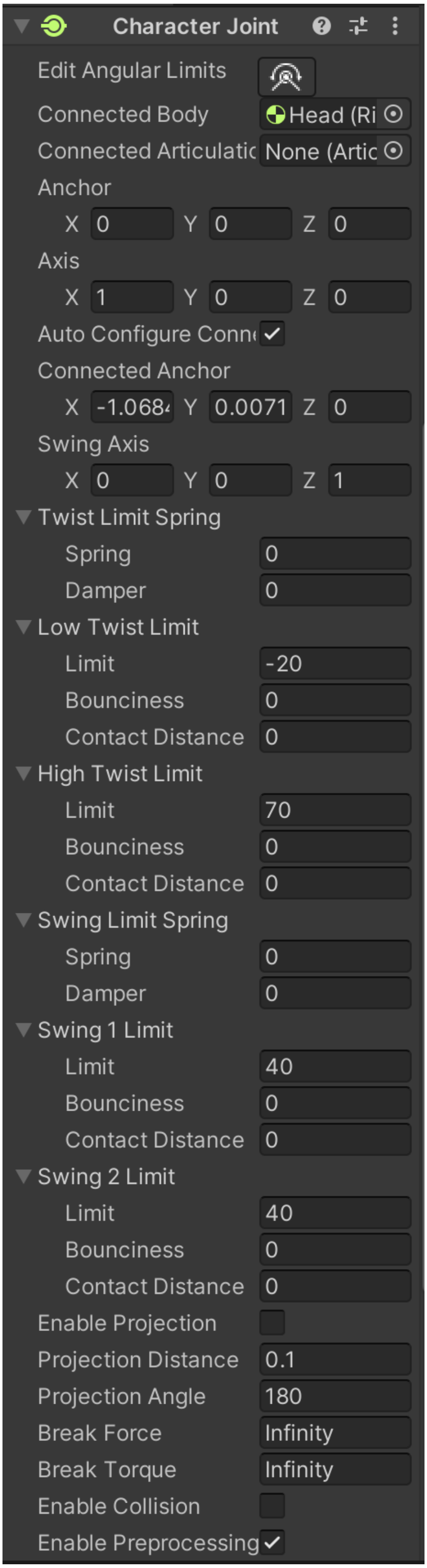

Fig. 12: Character joint parameters

Fig. 13: Comparing simulation and physical environment

DISCUSSION AND CONCLUSIONS

The preliminary results show that a DES model was suitable for setting up the experiments and developing the simulation model and that it is possible to virtually recreate and represent a fish with realistic behavior. The work, however, needs to be validated with quantitative data. Below is a list of parameters the authors foresee as being necessary to represent a fish and its behavior virtually: - Static and kinetic friction in 4 directions (along the fish length from head to tail and tail to head) and across the fish length (from back to belly and belly to back) - Weight distribution across the different body parts - Maximum angles along the three axis (roll, pitch, yaw) - Including the angle gradient along the fish length - COG of the fish - Standardized method of measuring length and weight

The authors also suspect that many of these variables will change with time from harvest and death. The rigor progress, for instance, will impact the friction between joints and their maximum angle due to the varying stiffness of the fish. In addition, the friction along the fish, both static and kinetic, will change with time and the mucus layer. Mapping these variables over time and creating time-dependent functions are necessary for further work to accurately represent a fish within a virtual realm, if it is at all possible to do. In this research, the rigidity of the fish was only measured right after slaughter, so the impact of rigor was not considered. As the testing with real fish was performed with fish that had been dead for more than one day, they likely did not have the same rigidity as the measured and simulated fish. Furthermore, the parameters may be impacted by the season, feed, capture, transportation, and slaughtering methods.

In future research, the authors suggest developing standardized measurement methods to capture the fish parameters needed to design a virtual fish, such as the work done at Ålesund Biomechanics Lab. Further, the authors recommend testing the method on more fish species.

ACKNOWLEDGEMENTS

This research is funded by the Norwegian Research Council “Fish 4.0”-project (Grant #331829). Further thanks to Optimar for providing a physical test environment and fish for testing, and performing the tests at their location.

References

[1] Statistics Norway, "Export of salmon - SSB," 2018. [Online]. Available: https://www.ssb.no/en/laks

[2] EHEDG Secretariat, "Doc 8 - Hygienic equipment design criteria," European Hygienic Engineering and Design Group (EHEDG), Frankfurt, Germany, Tech. Rep., 2004.

[3] ——, "Doc. 44 Hygienic Design Principles for Food Factories," EHEDG, Tech. Rep., 2014.

[4] H. Lelieveld, M. Mostert, and G. Curiel, "Hygienic design of food processing equipment," in *Hygiene in Food Processing*. Elsevier, 2014, ch. 4, pp. 91–141. [Online]. Available: http://dx.doi.org/10.1533/9780857098634.2.91

[5] P. S. Kleppe and O. Bjelland, "Implementation of Virtual Concurrent Engineering Tools in Engineering Education 4.0," in *IEEE Global Engineering Education Conference, EDUCON*, vol. 2022-March. IEEE Computer Society, 2022, pp. 189–194.

[6] P. S. Kleppe, A. F. Dalen, and W. Rekdalsbakken, "A novel way of efficient adaption of orthopaedic braces using 3D technology," in *Proceedings - 2018 IEEE Industrial Cyber-Physical Systems, ICPS 2018*. Institute of Electrical and Electronics Engineers Inc., 6 2018, pp. 345–350.

[7] P. S. Kleppe and W. Rekdalsbakken, "AUTOMATIC PRODUCTION OFPATIENT ADAPTED ORTHOPAEDIC BRACESUSING 3D -MODELLING TECHNOLOGY," in *Proceedings of the 34th International ECMS Conference on Modelling and Simulation*. ECMS, 2020.

[8] O. Bjelland, B. Rasheed, H. G. Schaathun, M. D. Pedersen, M. Steinert, A. I. Hellevik, and R. T. Bye, "Toward a Digital Twin for Arthroscopic Knee Surgery: A Systematic Review," pp. 45 029–45 052, 2022.

[9] J. Banks, J. S. Carson II, B. L. Nelson, and D. M. Nicol, *Discrete-Event System Simulation*, 5th ed. Pearson, 2010.

[10] S. Jain, "Simulation in the next millennium," in *Proceedings of the 31st conference on Winter simulation Simulation—a bridge to the future - WSC '99*, vol. 2, no. 3. New York, New York, USA: ACM Press, 1999, pp. 1478–1484. [Online]. Available: http://portal.acm.org/citation.cfm?doid=324898.325306

[11] M. Rohrer, "Seeing is believing: the importance of visualization in manufacturing simulation," in *2000 Winter Simulation Conference Proceedings (Cat. No.00CH37165)*, vol. 2, no. Riis 1995. IEEE, 2000, pp. 1211–1216. [Online]. Available: http://ieeexplore.ieee.org/document/899087/

[12] L. A. L. Giske, T. Benjaminsen, and O. J. Mork, "Prototyping installation and commissioning of novel a cleaning robot by using virtual tools – lessons learned," *Procedia CIRP*, vol. 00, 2019.

[13] A. M. Law and W. D. Kelton, *Simulation & Analysis*, 2013, no. October.

[14] K. J. Musselman, "Guidelines for simulation project success," *Proceedings of the 1994 Winter Simulation Conference*, pp. 88–95, 1994.

[15] J. Nagle, "US6067096A Method and system for generating realistic collisions in graphical simulations," 3 1998. [Online]. Available: https://worldwide.espacenet.com/patent/search/family/021878975/publication/US6067096A?q=pn%3DUS6067096

[16] Belnder, "blender.org - Home of the Blender project - Free and Open 3D Creation Software." [Online]. Available: https://www.blender.org/

[17] webGL, "WebGL Overview - The Khronos Group Inc." [Online]. Available: https://www.khronos.org/webgl/

AUTHOR BIOGRAPHIES

PAUL STEFFEN KLEPPE is assistant professor at NTNU, Norwegian University of Science and Technology, in Aalesund. He has a master degree in Mechanical Engineering and a MBA in Technology management from NTNU. Industrial background from industrial engineering and has 10 years of teaching experience in 3D-modelling and simulation at NTNU Aalesund.

LARS ANDRE GISKE has a master's degree in product and system design from NTNU and defended his PhD "Robotic Cleaning of Fish Processing Plants" in 2020. He has more than 10 years experience from the Norwegian Aquaculture industry and currently holds the position as Head of R&D at OPTIMAR AS and a Professor 2 guest lecturer at NTNU Aalesund.

OLA JON MORK is a professor at NTNU within Manufacturing and lean at NTNU Aalesund, and has the last five years been managing the research project "Robot Cleaning of fish processing factories and fish processing equipment" and several other projects within the fish industry. He has long experience as an industry leader, and has a master's in industrial technology and economy.

IRINA-EMILY HANSEN Irina-Emily Hansen is a researcher at the Department of Ocean Operations and Civil Engineering at NTNU. She holds a PhD in Knowledge Management of Industry-Academia Collaboration and a MSc in Product and System Design from NTNU, as well as MSc in System Engineering from St. Petersburg State Academy for Aerospace Engineering. She is project manager for Industry 4.0 Manufacturing lab (Manulab/Idelab in Ålesund. Irina-Emily is also coordinator for the project 'the Pathway to zero-emission in the World Heritage fjords', a collaboration between Stranda municipality, industrial partners and NTNU.