Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 00 (2021) 000–000

www.elsevier.com/locate/procedia

54th CIRP Conference on Manufacturing Systems

Development and Implementation of a Digital Manufacturing Demonstrator for Engineering Education

Shane Keaveney[a,*] Lydia Athanasopoulou[b] Vasilis Siatras[b] Panagiotis Stavropoulos[b] Dimitris Mourtzis[b] Denis P. Dowling[a]

a Univeristy College Dublin, Dublin, Ireland

b Laboratory for Manufacturing Systems and Automation, Department of Mechanical Engineering and Aeronautics, University of Patras, Patras 26504, Greece

* Shane Keaveney. Tel.: +35317161884; fax: *E-mail address:* shane.keaveney@ucd.ie

Abstract

The fourth industrial revolution (Industry 4.0) offers enhanced processing efficiencies and reduced downtime, however there is a lack of manufacturing training equipment for those seeking practical training in the key underpinning digital technologies. This paper reports on the development of a digital manufacturing training demonstrator, called the PERFORM turbine demonstrator, which incorporates four aspects of Industry 4.0, that of the Internet of Things (IoT), Augmented Reality (AR), the digital twin and additive manufacturing (3D printing). The program involves the printing of a polymer turbine and its testing using a turbine demonstrator system. This incorporates the use of an Arduino controller, sensors to monitor the systems variable pump speed, turbine speed, temperature and humidity. A cloud-based platform allows for data logging and passing to the AR application, visualization and system control. The design and development of the system is presented, alongside the results of pilot training programmes involving undergraduate engineering students, along with industry trainees on the practical application of Industry 4.0. This paper demonstrated the effectiveness of the PERFORM demonstrator in successfully integrating different digital technologies in the same system.

Keywords: IoT: Augment Reliaty: 3D printing: Engineering education:

1. Introduction

With the enhanced use of digital technologies in manufacturing there is an increased need for training in the application of these technologies. While there have been reports of individual technology demonstrators such as in 3D printing and virtual reality [1]–[3], there is also the need to demonstrate the enhanced performed which can be achieved through the integration of a number of different digital technologies, within a single manufacturing system.

In order to support trainees in Industry 4.0, it will require a transition from the traditional education model towards advanced concepts in the context of digitalisation, focusing on developing skills and digital competences particularly amongst young practitioners [4]. Digital skills training is also vital for both undergraduate engineering students, as well as those currently working within the manufacturing sector[5], [6].
During the design of a training program, considerations around trainee learning styles are very important. Coffield defined a learning style as an individual's unique approach to learning based on strengths, weaknesses, and preferences [7]. As reported by Gardener the learning styles are: logical-mathematical, linguistic, musical, spatial, bodily-kinesthetic, interpersonal, and intrapersonal [8]. Although individual learning styles are difficult to apply within a large class groups, content can be created or presented in different formats that appeal to different styles. By presenting educational content in a learner’s style, opposed to only a single style, their

knowledge, absorption, retention, and self-confidence can improve. Another important approach to achieving an enhanced learning experience as highlighted by Kapur, is “productive failure” [9]. The developed system reported within this paper will considered the above, presenting content through multiple mediums and methods, whilst also allowing for productive failure during the learning activity.

In addition to 3D printing, amongst the Industry 4.0 technologies that are of growing importance are the use of Internet of Things (IoT), process sensorisation, Augmented Reality (AR), Virtual Reality (VR) and the digital twin [10]–[12]. IoT and sensorisation allows engineers and scientists to gain new levels of knowledge and data about productivity aspects as well deep insights into processes. Thus, creating opportunities for increased productivity and detection of process anomalies or trends which could negatively affect manufacturing quality for example. The use of AR/VR technologies has multiple applications within an industrial setting, such as for visualization of complex assemblies/systems or assistance in the assembly process [13]–[15]. However, these technologies can also be used for the viewing of real time data, such as that generated and managed through sensorisation and IoT infrastructure respectively [16]. AR technology is also being used within education, to increase interactivity and attract the interest of students through a user-friendly environment [3], [17]. AR/VR technologies achieve an advanced form of visualizing various geometries of products and mechanisms, enabling interactivity and facilitating knowledge transferring in education [18].

The bringing together of a number of different digital technologies which are core to Industry 4.0, into a single education demonstrator system called PERFORM, is the focus of this paper. This PERFORM turbine system facilitates the demonstration of the following digital manufacturing technologies – additive manufacturing (3D printing), IoT, AR, and the digital twin, into a practical learning experience. This paper reports on the development and evaluation of the developed system. Two training studies were undertaken to evaluate the system, one with a large group of engineering students and a second with a group of industry trainees. Both training studies were aimed at evaluating the relevance of the demonstrator and associated program for industrial training.

2. Mythology

2.1. PERFORM Turbine Demonstrator Design

A schematic diagram of the PERFORM turbine demonstrator is given in Fig. 1. We have previously reported on the use of a turbine test system to evaluate the performance of 3D printed polymer turbines [19]. This study demonstrated that the use of the turbine test device to enabled undergraduate students to obtain direct feedback of their designs’ performance. It also allowed the students who were not familiar with 3D modelling, design and printing to gain these competencies.

Fig. 1. Photograph of the PERFORM turbine demonstrator. The turbine is mounted in the housing and as it rotates, it in turn rotates a spindle and the number of rotations (rpm) is monitored, based on the speed of the fly wheel.

Building on this original demonstrator, a redesign was undertaken to incorporate control and sensorisation of the major system inputs and outputs. This involved the inclusion of a variable speed air pump with pump sensor feedback, with an Arduino used to control and monitor the system. The Arduino was then linked to an online cloud service and an AR application build to go with the system. Fig. 2 shows a CAD design of the main system components excluded the electronics housed underneath.

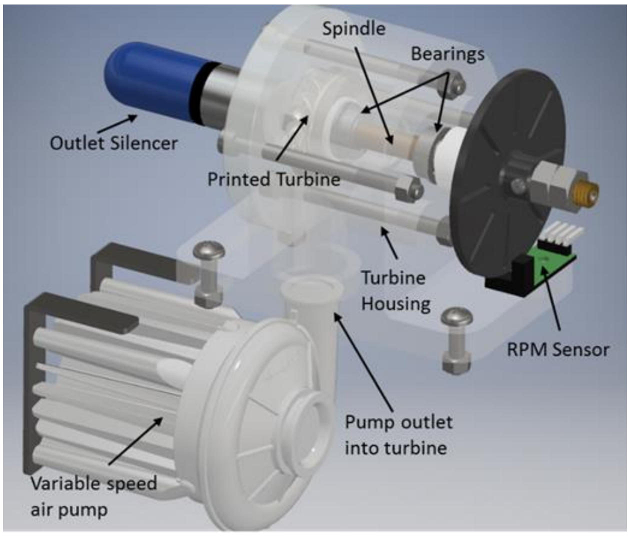

Fig. 2 Schematic of the PERFORM turbine demonstrator, illustrating how the rotational speed of the turbine is influenced by the air pressure generated by the pump.

Once the polymer turbine is designed and printed and tested using the turbine system, its performance was evaluated at a range of air pressures, by systematically alter the turbine speed using a variable speed air pump. Using an Arduino controller, sensor data on the pump speed, turbine speed, temperature, acoustics and humidity could be obtained. A cloud-based platform allows for data logging and passing to the AR application, visualization and system control. A graphical overview of the systems data flow diagram is shown in Fig. 3.

Reading of the sensors was carried out using an Arduino and a custom electronics shield, whilst the air pump flowrate was controlled by the Arduino using a digital potentiometer. The IoT was facilitated by combining the WIFI enabled Arduino MKR and the AllThingsTalk SDK for bi-directionally communication with the AllThingsTalk website [20]. The device is linked to an AllThingsTalk account through a unique device ID and token which is programmed into the Arduino's program (Fig. 3). This makes it easy to reconfigure the Arduino to talk to different AllThingsTalk accounts.

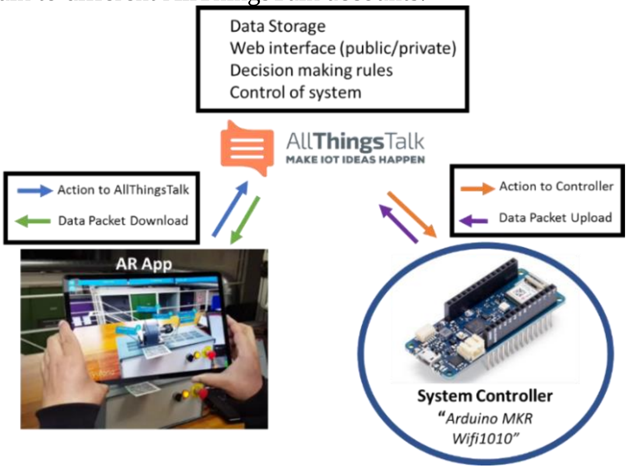

Fig. 3. Overview of data flow from the AR application, Arduino and AllThingsTalk platform for the PERFORM turbine demonstrator.

Once connected to an AllThingsTalk account the Arduino can send and receive data, for example sending real time sensor readings to the cloud storage or receiving commands from AllThingsTalk. AllThingsTalk allows for easy construction of a customisable Graphic User Interface (GUI) called a Pinboard, as well as communication with other sources or devices. The Pinboard can be private and/or shared publicly with easy visualisation of data and handling of user inputs.

2.2. PERFORM Turbine Demonstrator AR Application Development

The AR application enables digital holograms to blend with the turbocharger physical system's components, establishing a powerful tool for real-time performance monitoring and operational support. The scope of the application is to provide a more realistic and user-friendly environment for facilitating the monitoring and assembly process during the operation of the turbocharger demonstrator. To this end, multiple application's instances running simultaneously on multiple mobile devices and tablets, deliver a collaborative monitoring experience to students by either having access to the lab and the physical system of the turbocharger, or by monitoring its performance remotely.

Live streaming of the sensor data during the operation of the turbocharger is provided. The application delivers to students the ability to broadcast information related to the system's operation through the AllThingsTalk server and then project it in the AR environment, upon the physical component from which it derived. Such information is related to the current and speed of the motor, the microphone amplitude, the outlet flow, temperature and humidity etc. Additional data scattering and explanatory information about the different components and sensors can be triggered by the user to obtain a descriptive overview of the operation and performance of the turbocharger.

The AR application further provides step-by-step guidance during the assembly and disassembly process of changing the turbine blade component of the turbocharger. It is embedded with the ability to project and animate different component models, providing students with a sequence of instructions for changing and examining the performance of the turbocharger using different turbine designs. In particular, the user can select among four different turbine blade designs and holographic, user-triggered, steps are being projected to unmount and mount the interfering components. Therefore, in terms of educational level, students go through different assembly and disassembly tasks more easily as well as they are obtaining a better insight on the system. Emerging even more towards this aspect, a 3D model inspection virtual environment was developed to provide a thorough inspection of the entire components of the virtual model of the turbocharger. The user may use simple tag/drag gestures to inspect the digital model and obtain access to the hidden components and devices that consist the system. An example view of the AR application is seen in Fig. 4.

Fig. 4. Indicative view of the AR application showing real-time data display and turbine blade design selection.

The PERFORM AR application was developed to provide a clear insight to the turbocharger system for the users that have access to the physical demonstrator, as also providing the capability of monitoring its performance remotely without requiring in situ supervision. To this end, significant capabilities are provided in terms of eliminating the geographical barriers and promoting collaboration among students of different countries and locations. The remote mode of the application supports the real-time data streaming and monitoring to the physical system, providing a virtual representation of the physical turbocharger in the real environment. The superimposing of the virtual model of the turbocharger to the environment of the user provides an enhanced simulation of the physical system, delivering to students a close-to-reality experience and inspection of the demonstrator without requiring their presence to the lab.

The development of the application was based on Unity Engine and Microsoft Visual Studio (VS), for building the different functionalities and interactions between the user, the AR environment and the AllThingsTalk server. The application's infrastructures were based on CSharp programming language (.NET Framework), using Object Oriented Programming (OOP) for the development of the different entities for the AR environment. Vuforia Engine was also used to support the smooth interference of the digital and physical world, while using different Image Targets (QR-codes) for the spatial anchoring and cognitive projection/ stabilization of the AR objects in the scene. The communication between the application and the AllThingsTalk server, was achieved with the development of a MQTT client functionality, running asynchronously at the backend of the application's interface, and subscribing to a specific

AllThingsTalk ground ID, waiting for new information to be uploaded. The proposed protocol, enabled fast information exchange between the server and the AR application, allowing multiple sensor data to be visualized within the AR environment at a very high FPS rate.

2.3. Turbine Blade Design and Printing

A Fused Filament Fabrication (FFF) 3D printer was use for the fabrication of the turbine blades. A Stainless-Steel blade was also printed using Selective Laser Melting (SLM) in Stainless Steel 316L on a Concept Laser MLab to demonstration the industrial application of the demonstration. Polylactic Acid (PLA) filament were used for turbine blade part printing. Blade design was carried out on Autodesk Inventor, with Autodesk's suite of design, manufacturing, and simulation software and educational tutorials also used to assist in the design activity [21]. The critical blade dimensions are shown in Table 1. *Ulitmaker's Cura* open-source software was used for slicing.

Table 1. Turbine Fixed Parameters

Turbine Blade Feature	Fixed Parameters
Turbine base Thickness	1 mm
Turbine Diameter	Ø35.5 mm
Turbine Height	7 mm
Inner Ring Diameter	Ø14 mm
Turbine Base Mounting Hole Diameter	Ø9 mm
Turbine Top Mount Hole Diameter	Ø6 mm

2.4. Case Study

The evaluation of the Industry 4.0 training associated with the use of the PERFORM turbine demonstrator was assessed based on feedback from two groups of trainees. These were undergraduate engineering students and trainees from industry. In the case of the former 110 students were trained while in the case of the industry trainees, 28 received training from 20 companies. The latter was delivered to the trainees in two countries Spain and Ireland, simultaneously. Both the undergraduate students and industry trainees received a combination of lectures on Industry 4.0, practical training on part design and then the application of the learnt skills in the printing of a turbine. After printing, the turbine performance was evaluated on the PERFORM demonstrator, which included the demonstration of printed turbine performance based on the output from the system sensors (using IoT). The sensor data was available on the student's own devices (i.e. mobile phones), facilitated using an AR application. Based on a range of experimental studies carried out using the turbine system, anomaly data has been generated and this is made available to the students, to help to demonstrate the use of a digital twin approach.

For both the undergraduate and industry trainees' introductory lectures were given on the background and impact of Industry 4.0 as well as on topics such as sensor technology, IoT, AR additive manufacturing and the use of a digital twin. More applied training was provided in the design of parts for additive manufacturing along with printing processes. In order to support the design of the turbine by the students, they were provided with a number of journal papers which provided examples of factors influencing the performance of turbines[22]–[25]. These papers detailed how turbine design parameters such as the number of blades, blade shape and angle influenced turbine performance.

It was planned to deliver the training content to both the undergraduate students and industry trainees through direct face-to-face training, however this was not feasible due to the Covid-19 pandemic. A 'blended' training programme was therefore developed in which for the undergraduate students the training was delivered partially on-line, while for the industry trainees the delivery was fully on-line. In the case of the undergraduate the printing of the turbine parts was carried out directly with them in the laboratory. In the case of the industry trainees however this was carried out remotely with the trainees being able to see the printing of a demonstrator turbine over a 40-minute period, through the use of a camera which was used to monitor the printer. For the turbine design the students and trainees were divided into groups of 4, in order to propose a design for the turbine. They were asked to develop a STL file of the turbine device to be printed. After printing the turbine performance was monitored using the turbine demonstrator. The trainees were able to evaluate the performance of their turbine designs in real time on the downloader AR application. The use of the IoT and AR technologies to capture data on the performance of the turbine blades was made available on the mobile phone / tablet devices of both groups. In order to facilitate this detailed notes were provided for the relevant software and content, for example the use of www.AllthingsTalk.com, an IoT website that allows devices to talk to it for data storage and visualisation, how to download and operate the AR mobile application, Autodesk Inventor and Ultimaker Cura software used for fabricating the turbine blade [21], [26]. Tutorial videos were also provided for prepare and made available to assist in this step. The students were given all the required information to understand the IoT demonstrator itself and minimal input on the blade design, forcing them to research and use their own knowledge.

Pre and post surveys were taken to provide information on student prior knowledge in 3D modelling, IoT, AR/VR and additive manufacturing. These surveys also informed about the interest and relevance of the activity, value in relation to IoT, additive manufacturing and sensorisation. The study was conducted as an intervention case study with only quantitative data collect to monitor the learning experience and evaluate the impacts. The survey is influenced by Meyers work looking at the introduction of design through 3D printing [27]. The survey questions are detailed in the results section with a Likert scale used.

3. Results and discussion

As outlined earlier the developed PERFORM turbine demonstrator training was trialed with both undergraduate engineering students, as well as a group of industry trainees. The group of 110 students was used as the main assessment of the system as an intervention, with the industrial group used to gain insight on the relevance of the content and training for industry. For the student group a presurvey was taken to quantify their knowledge levels. As demonstrated in Table 2, some students had prior knowledge of 3D printing and modelling but returned a median of 2 and 3 respectively. Knowledge of AR/VR and sensors for monitoring was relatively low, with respective medians of 1 and 2, with 55.8% of students stating no knowledge of AR/VR. A number had knowledge of Industry 4.0 with most also enjoying typical engineering labs. The 28 industry trainees from both Spain and Ireland were based in manufacturing engineering companies.

Table 2. Pre-survey responses from the group of 110 engineering students

Pre-Survey	No Knowledge				Substantial Knowledge	Median
Q1	10.5%	41.1%	33.7%	12.6%	2.1%	2
Q2	4.2%	20.0%	44.2%	25.3%	6.3%	3
Q3	55.8%	30.5%	9.5%	4.2%	0.0%	1
Q4	39.4%	38.3%	18.1%	4.3%	0.0%	2
Q5	6.3%	24.0%	51.0%	17.7%	1.0%	3
	Not at all				Very much	
Q6	0.0%	2.1%	16.8%	51.6%	29.5%	4

Pre-Survey Questions:

Q1: What is your experience with 3D printing?

Q2: What is your experience of 3D modelling?

Q3: What is your experience of AR/VR technologies?

Q4: What is your experience of using sensors for real time monitoring?

Q5: Rate your overall understanding of Industry 4.0?

Q6: Do you enjoy typical engineering Labs?

After completion of the training, a post survey was carried out for both groups of trainees. This survey had two sections, the first focused on learning impact of the course Q1 – 5 and the second more generally on the learning experience Q6 – 11.

Table 3. Post-survey student responses related to understanding.

Post Survey	Strongly Disagree		N/A		Strongly Agree	Median
Q1	0.0%	1.1%	10.8%	61.3%	26.9%	4
	Very low				Very high	
Q2	0.0%	1.1%	16.3%	59.8%	22.8%	4
Q3	0.0%	8.8%	30.8%	48.4%	12.1%	4
Q4	0.0%	3.3%	20.7%	59.8%	16.3%	4
Q5	1.2%	7.3%	36.6%	50.0%	4.9%	4

Post-Survey Questions:

Q1: Indicate to what extent you agree: By taking this course I gained significant experience in the design process

Q2: Indicate the extent to which this course assisted in the understanding of the steps in component manufacturing

Q3: Indicate the extent to which the AR app assisted in your understanding of the system

Q4: Indicate the extent to which realtime monitoring assisted in your understanding of the turbine system

Q5: Rate your overall understanding of 4.0

Table 4. Post-survey student responses related to learning experience.

Post Survey	Not at all				Very much	Median
Q6	0.0%	0.0%	3.3%	41.3%	0.0%	5
Q7	0.0%	2.2%	5.4%	44.6%	0.0%	4
Q8	0.0%	0.0%	7.8%	43.3%	0.0%	4
Q9	0.0%	4.3%	9.8%	47.8%	0.0%	4
Q10	1.1%	8.9%	13.3%	55.6%	1.1%	4
Q11	0.0%	7.7%	18.7%	51.6%	0.0%	4

Post-Survey Questions:

Q6: Was this an interesting learning experience?

Q7: Was this a relevant learning experience?

Q8: Was this a valuable engineering design experience

Q9: Has this increased your interest in 3D printing technologies?

Q10: Has this increased your interest in using sensors for realtime monitoring?

Q11: Has this increased your interest in AR/VR technologies?

For the student group the results of this survey are seen in Table 3 and

Table 4. Generally, the results show a positive impact of the training, with enhanced interest in the 3D printing, sensorisation, IoT, and AR/VR with a median of 4 achieved for all questions, apart from question 6 which returned a median of 5. It is noted however that although the median of question 5, related to understanding of IoT is 4, 36.6% of the response returned a score of 3. One of the major focuses of the course is to gain knowledge in IoT so this should be investigated further.

Table 5. Post-survey industry group response related to understanding.

Post Survey	Strongly Disagree		N/A		Strongly Agree	Median
Q1	0%	0%	20%	70%	10%	4
	Very low				Very high	
Q2	0%	0%	10%	80%	10%	4
Q3	0%	0%	30%	40%	30%	4
Q4	0%	10%	30%	20%	40%	4
Q5	0%	0%	30%	40%	30%	4

Table 6. Post-survey industry group responses related to learning experience.

Post Survey	Not at all				Very much	Median
Q6	0%	0%	0%	30%	70%	5
Q7	0%	0%	20%	50%	30%	4
Q8	0%	0%	10%	70%	20%	4
Q9	0%	0%	0%	40%	60%	5
Q10	0%	0%	0%	50%	50%	4.5
Q11	0%	0%	10%	60%	30%	4

For the student group the results of this survey are seen in Table 3 and

Table 4. Generally, the results show a positive impact of the training, with enhanced interest in the 3D printing, sensorisation, IoT, and AR/VR with a median of 4 achieved for

all questions, apart from question 6 which returned a median of 5. It is noted however that although the median of question 5, related to understanding of IoT is 4, 36.6% of the response returned a score of 3. One of the major focuses of the course is to gain knowledge in IoT so this should be investigated further.

Table 5 and Table 6 present the results from the industry trainees. This again demonstrated a very positive feedback on the training experience. In the comments section however difficulties associated with downloading the IoT and AR software application, were highlighted by a number of the trainees. The median scores were high, with that for question 9 of 5, while that for question 10 was 4.5. This is an increase from the median of 4 report reported from the student group with 30% of the group report 5.

4. Conclusions

This paper reported on the development of the PERFORM turbine demonstrator system and its evaluation for the delivery of Industry 4.0 training to undergraduate students and industry trainees. The system has brought together several key education and industrial relevant digital manufacturing topics; IoT, AR/VR, 3D printing and the digital twin. The ability for students to download the IoT and AR applications onto their own devices and see the generated data in real-time was found to be particularly impactful. Incorporation of the developed AR application was shown to facilitate a visual learning style, particularly beneficial for some students. The strong student engagement and learning was supported by the survey results. It is concluded from these trainee surveys that the developed PERFORM turbine demonstrator has considerable potential as an Industry 4.0 education tool. The framework developed in PERFORM project could be further enhanced in future work such as application on more complex scenarios under the concept of Industry 4.0. This could deliver valuable knowledge and hands-on student experience, increasing their involvement in manufacturing and engineering.

Acknowledgements

This project was part funded by the EU funded EIT-Manufacturing 'PERFORM' project, and the Science Foundation Ireland (SFI) I-Form Centre under Grant Number 16/RC/3872. The authors would also like to acknowledge the support of Croom Precision Medical Ireland.

References

[1] S. Keaveney, C. Keogh, L. Gutierrez-Heredia, and E. G. Reynaud, "Applications for advanced 3D imaging, modelling, and printing techniques for the biological sciences," in *2016 22nd International Conference on Virtual System & Multimedia (VSMM)*, 2016, pp. 1–8.

[2] S. Ford and T. Minshall, "Invited review article: Where and how 3D printing is used in teaching and education," *Addit. Manuf.*, vol. 25, pp. 131–150, 2019.

[3] S. Antoniou, L. Rentzos, D. Mavrikios, K. Georgoulias, D. Mourtzis, and G. Chryssolouris, "A Virtual Reality Application to Attract Young Talents to Manufacturing," *Procedia CIRP*, vol. 57, pp. 134–139, 2016.

[4] D. Mourtzis, E. Vlachou, G. Dimitrakopoulos, and V. Zogopoulos, "Cyber- Physical Systems and Education 4.0 –The Teaching Factory 4.0 Concept," *Procedia Manuf.*, vol. 23, pp. 129–134, 2018.

[5] D. Mavrikios, K. Georgoulias, and G. Chryssolouris, "The Teaching Factory Network: A new collaborative paradigm for manufacturing education," *Procedia Manuf.*, vol. 31, pp. 398–403, 2019.

[6] P. Stavropoulos, H. Bikas, and D. Mourtzis, "Collaborative Machine Tool design: the Teaching Factory paradigm," *Procedia Manuf.*, vol. 23, pp. 123–128, 2018.

[7] F. Coffield, D. Moseley, E. Hall, and K. Ecclestone, "Learning styles and pedagogy in post-16 learning A systematic and critical review," *Learning*, p. 84, 2004.

[8] H. Gardner and T. Hatch, "Multiple Intelligences Go to School: Educational Implications of the Theory of Multiple Intelligences," *Educ. Res.*, vol. 18, no. 8, pp. 4–10, 1989.

[9] M. Kapur, "Productive Failure," *Cogn. Instr.*, vol. 26, no. 3, pp. 379–424, Jul. 2008.

[10] D. Mourtzis, F. Xanthi, and V. Zogopoulos, "An Adaptive Framework for Augmented Reality Instructions Considering Workforce Skill," *Procedia CIRP*, vol. 81, pp. 363–368, 2019.

[11] A. Y. C. Nee, S. K. Ong, G. Chryssolouris, and D. Mourtzis, "Augmented reality applications in design and manufacturing," *CIRP Ann.*, vol. 61, no. 2, pp. 657–679, 2012.

[12] G. Michalos, A. Karvouniari, N. Dimitropoulos, T. Togias, and S. Makris, "Workplace analysis and design using virtual reality techniques," *CIRP Ann.*, vol. 67, no. 1, pp. 141–144, 2018.

[13] O. Danielsson, M. Holm, and A. Syberfeldt, "Augmented reality smart glasses in industrial assembly: Current status and future challenges," *J. Ind. Inf. Integr.*, vol. 20, p. 100175, 2020.

[14] D. Mourtzis, V. Zogopoulos, and F. Xanthi, "Augmented reality application to support the assembly of highly customized products and to adapt to production re-scheduling," *Int. J. Adv. Manuf. Technol.*, vol. 105, no. 9, pp. 3899–3910, 2019.

[15] J. J. Roldán, E. Crespo, A. Martín-Barrio, E. Peña-Tapia, and A. Barrientos, "A training system for Industry 4.0 operators in complex assemblies based on virtual reality and process mining," *Robot. Comput. Integr. Manuf.*, vol. 59, pp. 305–316, 2019.

[16] M. F. Alam, S. Katsikas, O. Beltramello, and S. Hadjiefthymiades, "Augmented and virtual reality based monitoring and safety system: A prototype IoT platform," *J. Netw. Comput. Appl.*, vol. 89, pp. 109–119, 2017.

[17] N. Arulanand, A. R. Babu, and P. K. Rajesh, "Enriched Learning Experience using Augmented Reality Framework in Engineering Education," *Procedia Comput. Sci.*, vol. 172, pp. 937–942, 2020.

[18] D. Mavrikios, K. Alexopoulos, K. Georgoulias, S. Makris, G. Michalos, and G. Chryssolouris, "Using Holograms for visualizing and interacting with educational content in a Teaching Factory," *Procedia Manuf.*, vol. 31, pp. 404–410, 2019.

[19] S. G. Keaveney and D. P. Dowling, "Application of additive manufacturing in design & manufacturing engineering education," in *2018 2nd International Symposium on Small-scale Intelligent Manufacturing Systems (SIMS)*, 2018, pp. 1–6.

[20] ALSO, "AllThingsTalk," 2020. [Online]. Available: https://www.allthingstalk.com/. [Accessed: 15-Dec-2020].

[21] Autodesk, "Free Student Software Downloads." [Online]. Available: https://www.autodesk.com/education/free-software/featured. [Accessed: 14-Jan-2018].

[22] R. Adhikari and D. Wood, "The Design of High Efficiency Crossflow Hydro Turbines : A Review and Extension," *Energies*, vol. 11, no. 2, p. 267, 2018.

[23] M. F. Turbine and F. V. Method, "The Number Of Blade Effects On

The Performance Of A Mixed Turbine Rotor," *Eng. Rev.*, vol. 37, no. 3, pp. 349–360, 2017.

[24] L. Mueller, Z. Alsalihi, and T. Verstraete, "Multidisciplinary Optimization of a Turbocharger Radial Turbine," *J. Turbomach.*, vol. 135, no. 2, pp. 1–9, 2013.

[25] T. Sciences, "Effect of the Blade Curvature Angle to Power Generation on the Drag Type Horizontal Axis Water Turbine," *J. Adv. Res. Fluid Mech. Therm. Sci.*, vol. 49, no. 2, pp. 115–120, 2018.

[26] Ultimaker, "Ultimaker Cura 3D Printing Software." [Online]. Available: https://ultimaker.com/en/products/ultimaker-cura-software. [Accessed: 14-Jan-2018].

[27] K. L. Meyers, A. S. Morgan, and B. P. Conner, "3D printing to introduce design in a cornerstone project," *Glob. J. Eng. Educ.*, vol. 18, no. 1, pp. 22–29, 2016.