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Table of Contents

By Paper Title:

Applications of Bioinspiration in Additive Manufacturing 3

Design and Implementation of a PID-Controlled Heating System in a Virtual Reality Environment 20

Developing a holistic master's program in industrial technology focused on data and Industry 4.0 33

Engineering Technology Undergraduates Assisting Civil Engineering Research through Automation 44

Implementing a Leadership Matrix Framework for Technology Programs 54

Review of Commercialized Firefighting Robotics Technology 62

By Author:

Dr. Scott Abney 54

Mrs. Natalie Aman 54

Dr. Burchan Aydin 62

Boaz Burnett 44

Clay Goodman 44

Jake Hildebrant 44

Kouroush Jenab 20

Joseph D. Long Ph.D 3

Kay Morgan 33

Jorge A. Ortega-Moody 20

Swapnil Patole 33

Andres Salinas-Hernandez 20

John Wyatt 33

Applications of Bioinspiration in Additive Manufacturing

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Keywords: technology management, bioinspiration, additive manufacturing, 3d printing, rapid prototyping, compressive modulus of elasticity, compressive proportional limit, maximum compressive stress

Abstract

Currently additive manufacturing (AM) is still primarily used for prototyping and modeling. However, with the increase in available materials and more advanced machines, AM is becoming a production process in which ready-to-ship products are being manufactured, therefore it is important to effectively use the material in AM machines. One way this can be accomplished is by modifying the infill structure that is used. This proceeding reports the on the testing and statistical analysis of the compressive strength of chopped carbon fiber reinforced nylon specimens manufactured on an Ultimaker 2+ 3D printer. Using the honeycomb, truss, and gyroid designs are examples of bioinspiration, or the use of design in nature for solving engineering problems.

Introduction

Solving problems is an everyday occurrence. Problems happen, effective technology management professionals can solve them. When an exoskeleton is too heavy for a patient to even benefit from, additive manufacturing (AM) can be used to help solve this problem through bioinspiration using lightweight infill patterns and densities without compromising strength.

Additive manufacturing

In the 1980s, several researchers were exploring new ways of producing parts through AM, which is officially defined as the "process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies" (ISO/ASTM52900-15-3.1). Some of the potential advantages of AM that the French 3D printing company Sculpteo (2017) names are: the ability to manufacture complex designs not possible through subtractive manufacturing, produce less waste material, improve designs before making costly tooling, and integrating conformal cooling channels more efficiently. Additionally, Bikas, Stavropoulos, and Chryssolouris (2016) discuss the increased "design freedom" that AM offers by allowing engineers to redesign multi-part assemblies into one or two parts. Some of the industries that are using AM technology are the automotive, medical, and aerospace, to name a few. One reason for its use in the medical field is its high level of customization; take for instance dental implants, where a dental professional can 3D scan a patient's jaw and produce an implant that will fit perfectly.

In AM, objects are generally not printed as a solid object, they are made up of a shell with an internal latticework, referred to as infill, which is selected by the user and often has a pattern that is optimized to shorten print time and/or lightweight the part, while maintaining structural integrity (Wu, Aage, Westermann, and Sigmund, 2017). Furthermore, Chacóna, Caminerob, García-Plazab, and Núñezb (2017) explain that the printing parameters, two of which are the infill density and pattern, have a significant effect on the quality and strength of 3D printed objects. This research tested the hypothesis that bioinspired infill designs are more efficient, meaning that they have a higher compressive modulus of elasticity, compressive proportional limit, and maximum compressive stress at equal density, than a standard grid infill design.

Bioinspiration

> Although human genius through various inventions makes instruments corresponding to the same ends, it will never discover an invention more beautiful, nor more ready nor more economical than does nature, because in her inventions nothing is lacking, and nothing is superfluous.

These are the words of Leonardo da Vinci back in the early 1500s (as cited in Thompson, 1999, p. 23). Da Vinci recognized that design is all around us in the natural world. Biomimicry is defined as the technical emulation of biological forms, processes, patterns, and systems (Benyus, 2013); other terms that are used (often interchangeably) are bioinspiration, and biomimetics. Wegst, Bai, Saiz, Tomsia, and Ritchie (2015, p. 23) further explain that, "today, scientists and engineers continue to be fascinated by the distinctive qualities of the elegant and complex architectures of natural structures."

One of the inspirations that has come from the living world is the honeycomb design. This multicellular hexagonal configuration is a very effective design and has been heralded as the most efficient shape to fill a two-dimensional shape plane since at least around 36 BC when Marcus Terentius Varro wrote about the hexagonal shape of the bee's honeycomb (Hales, 2002). Furthermore, Chamberland (2015) commented that:

> A mathematical rational was given by the Polish polymath Jan Brożek (1585–1652): The hexagon tiles the plane with minimal boundary. Stated another way, Brożek conjectured that the optimal way to cover a large region with shapes of the same area while minimizing the boundary is to use the hexagonal structure. (p. 157)

The boundary that Brożek is referring to is the waxy perimeter of the structure, indicating that a honeycomb made of squares, for example, would take more wax than one made of hexagons. In a 2002 article, Hales was able to mathematically demonstrate the truthfulness of the Honeycomb Conjecture. Today the honeycomb is a widely used design with many applications, from the airfoils of planes to mattresses, and even packaging.

Another design that has been inspired from the living world is the truss system which can be found in the bones of birds, among other places. Novitskaya et al. (2017) report that the internal structure of many avian wings contains reinforcing structures called struts and ridges. Struts are the members that stretch across the internal walls of the bone while the ridges lie against the bone's wall. The results of these added structures are at least twofold: first, their bones are able to withstand the forces experienced in takeoff, flight, and landing, and second, maintaining a lightweight ratio. Often, the stresses experienced in the bird's bones are in the form of bending and torsion. It is believed that these reinforcing structures develop in response to the specific stresses experienced by the birds in takeoff, flight, and landing.

Novitskaya et al. (2017) scanned a condor femur and a turkey vulture humerus bone utilizing a micro-computed tomography scanner to analyze the internal structure. The research team then modeled, and 3D printed (in ABS material) hollow cylindrical tubes with struts along part of the interior wall to simulate the bird bone structure. Three samples were torsion tested on an Instron 3367 Dual Column Testing System, while three others were compression tested to test the effect of the ridges on ovalization. The results of the strength testing suggested that the struts had a noticeable effect on the ovalization or compressive strength, while the results of the torsion samples did not show a noticeable effect from the struts on the torsion forces.

The final bioinspired design to be considered in this proceeding is the gyroid. NASA scientist A. Shoen was the first to describe this structure in 1970 (Podroužek, Marcon, Ninčević, & Wan-Wendner, 2019). Schoen (1970, p. 48) stated that the gyroid structure "contains neither straight lines nor plane lines of curvature. Thus, its symmetry group includes no mirror reflections, and the axes of rotational symmetry do not lie in the surface." Gan, Turner, and Gu (2016, p. 1) describe gyroids as "chiral periodic structures with a cubic symmetry." A chiral structure is one which is not superimposable on its mirror image (Kahn Academy, 2019) and cubic symmetry refers to the geometric nature the unit cell of the gyroid (see Figures 1-3 below).

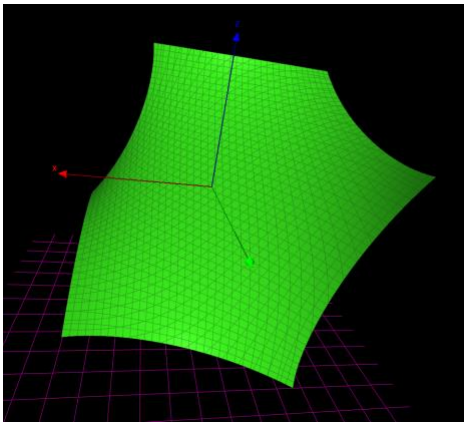


Figure 1. Gyroid. Single period of the gyroid structure as derived from the formula cos(x)*sin(y)+cos(y)*sin(z)+cos(z)*sin(x).

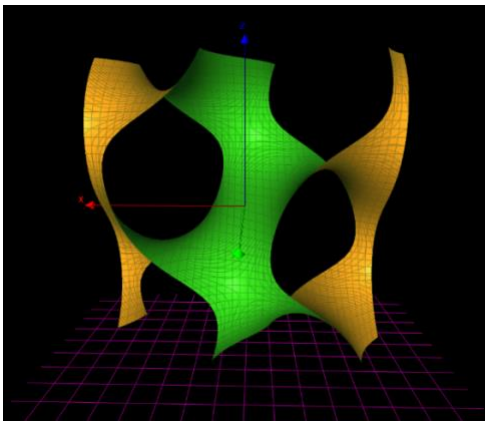


Figure 2. 3x1x3 Gyroid Structure.

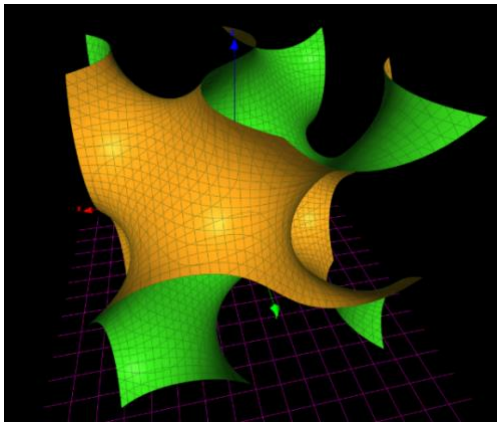


Figure 3. 3x3x3 Gyroid Structure.

The gyroid structure can be found in living and non-living systems. One example can be found in the wings of some species of butterflies. In the field of photonics and optics, researchers Gan, Turner, and Gu, (2016) used scanning electron microscopy to study the gyroid nano-structures found in the blue-green colored wings of the *Callophrys rubi* butterfly. Similarly, Goi, Cumming, and Gu, (2018, p.2) in their research described the butterfly wing as a natural gyroid with "two unequal sub-volumes, the largest filled with air and the smallest filled with cuticle." These air and cuticle filled structures are called biophotonic nanostructures and produce the iridescent structural colors that are seen on the butterfly's wings (Saranathan et al., 2010; Pouya et al., 2016). The "reflectance spectrum is determined by submicrometre structural variations causing interference, diffraction or scattering creating structural, physical colors" (Michielsen, & Stavenga, 2008, p. 85).

Methodology

Design of Experiment and Data Collection

A 2 x 4 independent factorial design was used to test the hypotheses for this quantitative experimental research project (see Figure 4). Field (2018, p. 449) states that this design is used when "there are several independent variables or predictors and each has been measured using different entities (between groups)."

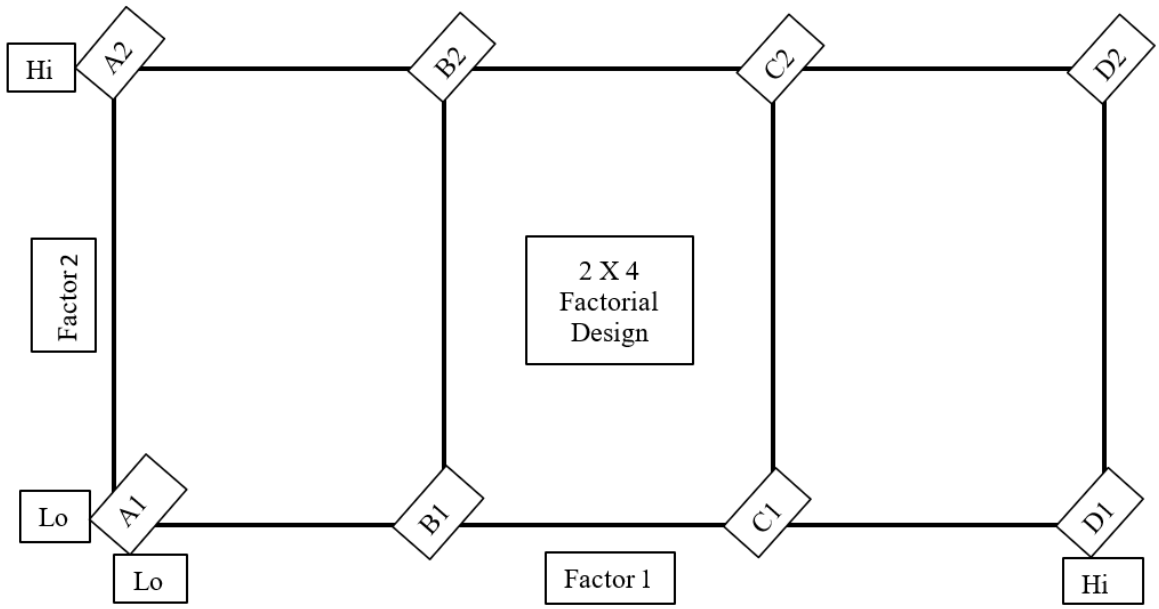


Figure 4. Group Divisions.

Variables and Data Recording Information

A 2 x 4 independent Factorial ANOVA was used to test the hypotheses. Table 1, shows the variables that were used in the statistical analysis. It contains two nominal dichotomous independent variables, and three nominal continuous dependent variables (measured in N/mm^2). The two independent variables are *infill design* and *infill density*. The dependent variables are the *compressive modulus of elasticity*, the *compressive proportional limit*, and the *maximum compressive stress*; these three dependent variables were calculated from the same data output that was produced in the compression testing of each specimen. The two factors and levels can be seen in Table 2.

Table 1.

Variables

	Independent / Dependent Variable	*Level of Measurement*	*Characteristics of Measurement*	*Levels*
Infill design	IV	Nominal	Dichotomous	1 = 2D Grid 2 = 2D Honeycomb 3 = 3D Truss 4 = 3D Gyroid
Infill Density	IV	Nominal	Dichotomous	1 = 30% Density 2 = 50% Density
Compressive Modulus of Elasticity (N/mm^2)	DV	Ratio	Continuous	(N/mm^2)
Compressive Proportional Limit (N/mm^2)	DV	Ratio	Continuous	(N/mm^2)
Maximum Compressive Stress (N/mm^2)	DV	Ratio	Continuous	(N/mm^2)

Table 2.

Group Divisions

Group	*Factor 1*	*Factor 2*
A1	2D Grid	30% Density
B1	2D Honeycomb	30% Density
C1	3D Truss	30% Density
D1	3D Gyroid	30% Density
A2	2D Grid	50% Density
B2	2D Honeycomb	50% Density
C2	3D Truss	50% Density
D2	3D Gyroid	50% Density

Figures 5 and 6 show the test specimens, with walls and top layers removed, in order to show the infill designs and infill densities. The 3D Truss infill design is not a standard infill design and thus was developed in 3DXpert for SolidWorks 14.0, see Figure 6.

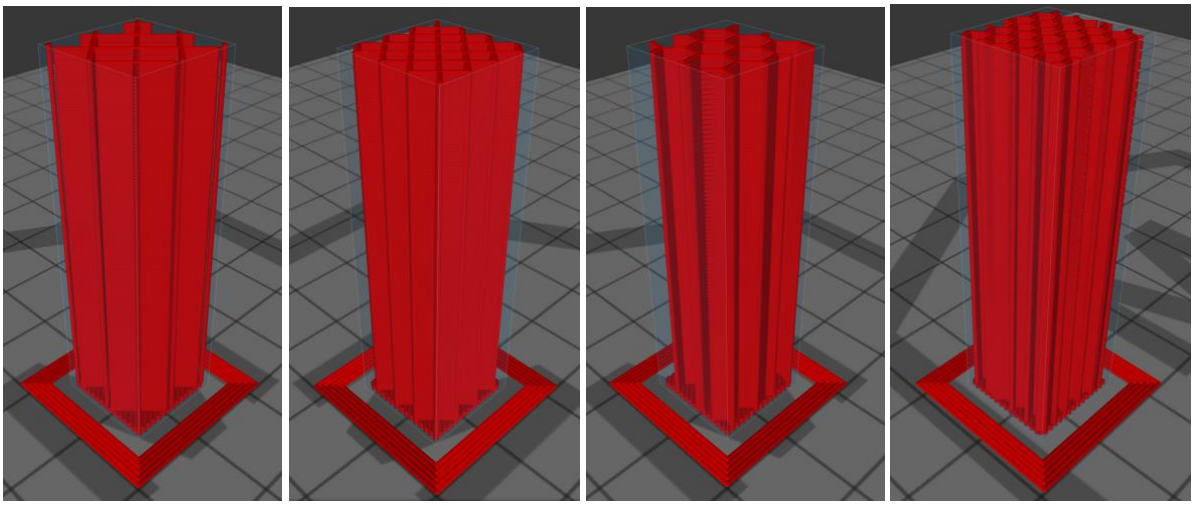


Figure 5. 3D Representation of Test Specimen. The difference in a 30% and 50% infill density can be seen in the images above (a) is the 2DGrid design at 30% density, (b) is the 2DGrid design at 50% density, (c) is the 2DHoneycomb at 30% density, and (d) is the 2DHoneycomb at 50% density.

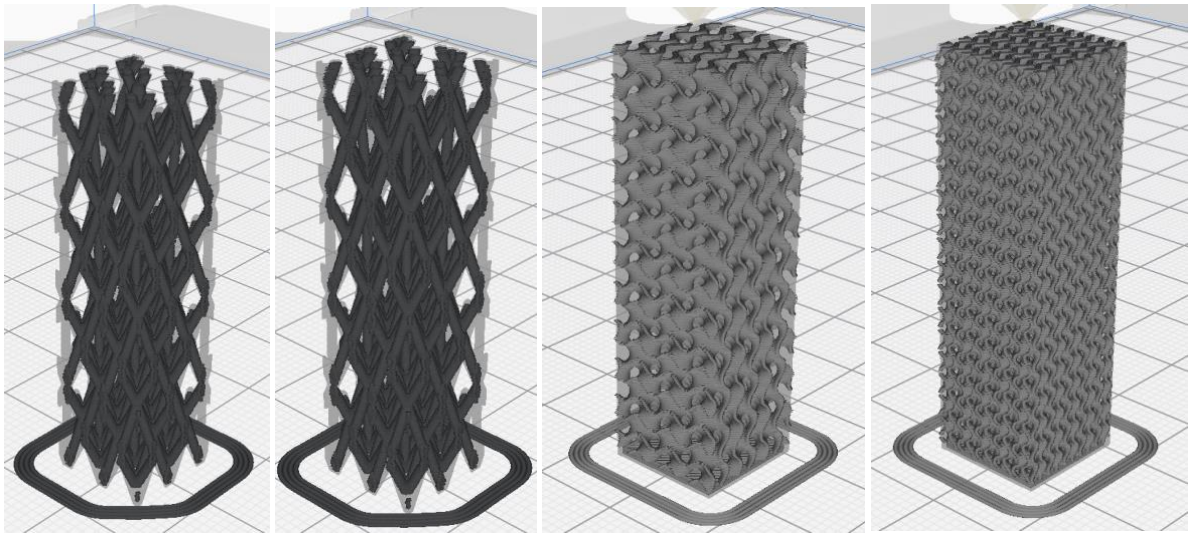
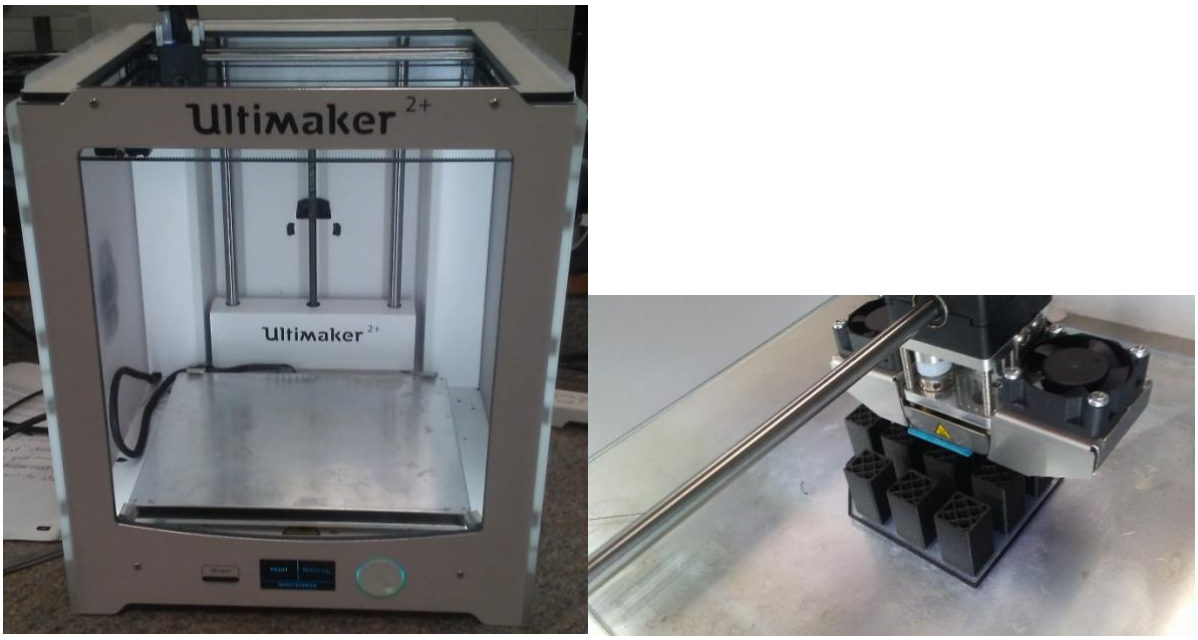


Figure 6. 3D Representation of Test Specimen. The difference in a 30% and 50% infill density can be seen in the images above (a) is the 3DTruss design at 30% density, (b) is the 3DTruss design at 50% density, (c) is the 3DGyroid at 30% density, and (d) is the 3Dgyroid at 50% density.

Two sets of ten test specimens and one set of five of each infill design and density were printed at a time, e.g. prints of ten and five A1s, A2s, B1s, B2s, and etcetera. A total of 200 test specimens will be printed, 25 of each infill and density combination: 25 – A1s, 25 – A2s,

25 – B1s, 25 – B2s, 25 – C1s, 25 – C2s, 25 – D1s, and 25 – D2s. Figure 8 show an example of build plates with ten and five specimens; the finished test specimens were each affixed with barcode labels for tracking purposes. As previously stated, an Ultimaker 2+ was used to print all 200 test specimens (see Figure 7).



a b

Figure 7. Ultimaker and Printing. Image (a) shows the 3D printer used to produce the 200-test specimen. Image (b) shows the Ultimaker building ten of the A1 prints.

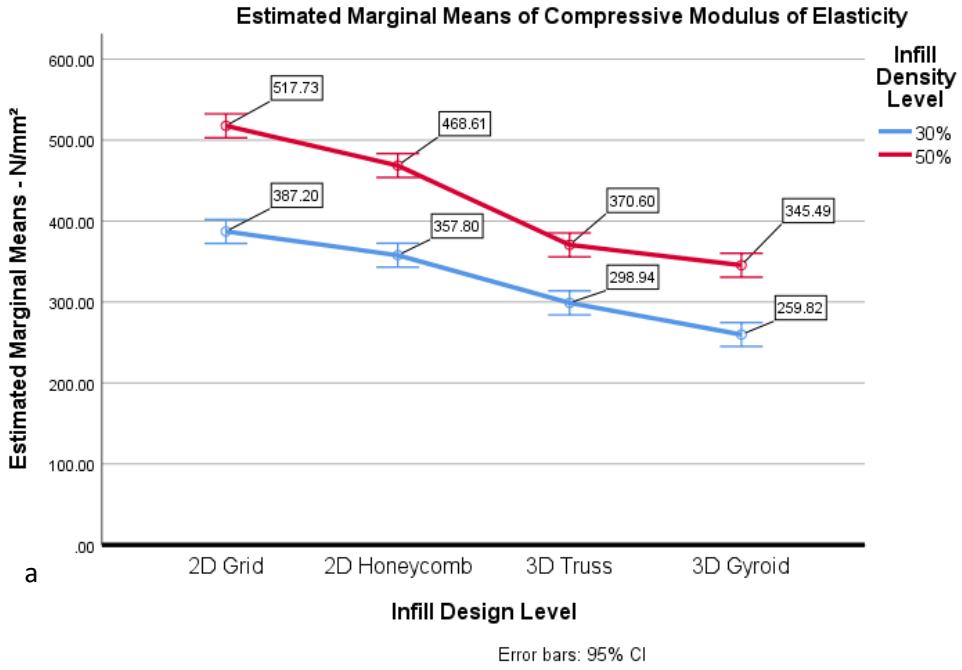
a b

Figure 8. Example of Build Plates. Test specimen were built in batches of ten (a) and five (b).

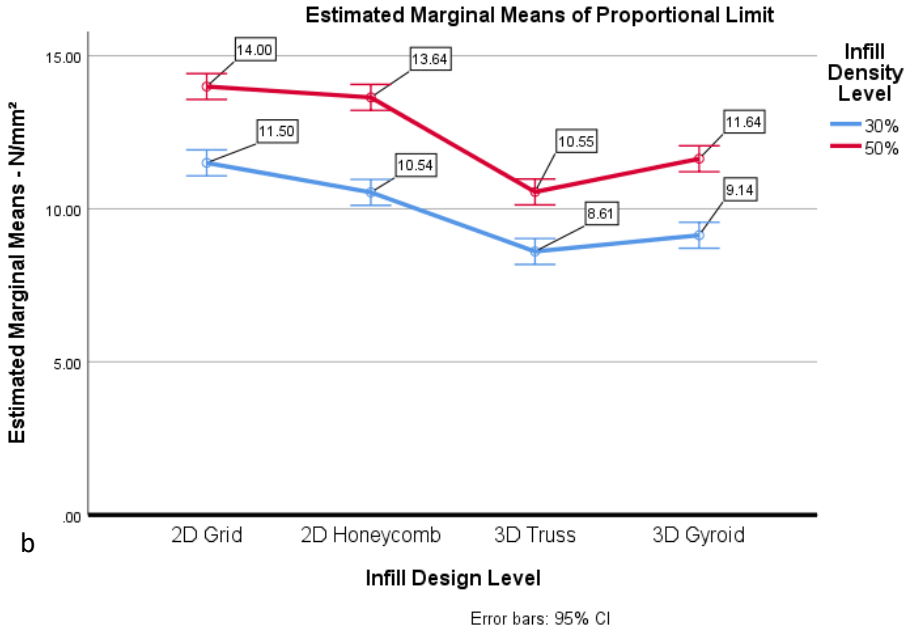
Discussion of the Results

Strength comparison by infill design and density

The following data, in Figures 9 and 10, is a general comparison showing the mean compressive modulus of elasticity, compressive proportional limit, and maximum compressive stress across the tested infill densities and infill designs. A visual observation of Figure 9 (Image a) suggests that if the compressive modulus of elasticity is of primary concern for a given part to be produced by AM, the 2D Grid infill design might be the first choice for the technology management professional at 30% or 50% infill density, followed by the 2D Honeycomb design, then the 3D Truss design, and lastly the 3D Gyroid design (if one is only selecting from the four designs used in this study). If the compressive proportional limit is of primary concern for a given part to be produced by AM, the data shown in Figure 9 (Image b) suggests that the 2D Grid infill design might be the first choice for the technology management professional, followed by the 2D Honeycomb design, then the 3D Gyroid design, and lastly, the 3D Truss design (if one is only selecting from the four designs used in this study). And finally, if the maximum compressive stress is the primary concern for a given part to be produced by AM, the data shown in Figure 10 suggests that the 2D Grid and the 2D Honeycomb infill designs are nearly equal (at 50% density) implying that either one may be a good first choice for the technology management professional, followed by the 3D Gyroid design, and lastly, the 3D Truss design (if one is only selecting from the four designs used in this study).



a



b

Figure 9. Estimated Marginal Means. Image (a) displays a plot of the data collected during the study for the compressive modulus of elasticity, while image (b) displays that of the compressive proportional limit.

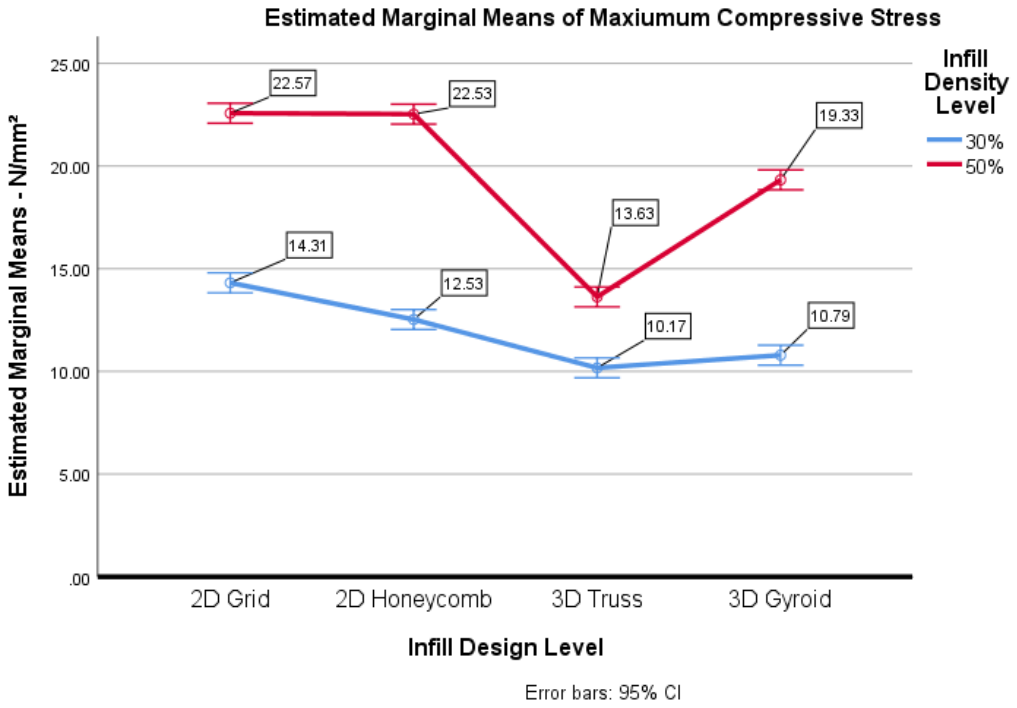


Figure 10. Estimated Marginal Means. This figure displays a plot of the data collected during the study for the maximum compressive stress.

As demonstrated in the results of this research, there is a statistically significant difference in the compressive modulus of elasticity, the compressive proportional limit, and the maximum compressive stress between levels for the infill density and infill designs. These significant differences indicate that technology management professionals should be careful when choosing an infill density and an infill design for a part to be produced by AM when the compressive modulus of elasticity, compressive proportional limit, and maximum compressive stress is a concern.

Practical implications and applications

Consequently, some practical implications of this research are the possibility that the selection of various levels of infill density and infill deign used to produce a given part through AM would result in a significantly higher or lower compressive modulus of elasticity, compressive

proportional limit, or maximum compressive stress. For technology management professionals conducting research in the field of AM, these results imply that further research will be necessary to determine the amount of variation assignable to infill density and infill design, as it effects the compressive modulus of elasticity, compressive proportional limit, or maximum compressive stress.

The interactions of 30% x 2Dgrid, 50% x 2Dgrid, 30% x 2Dhoneycomb, 50% x 2Dhoneycomb, 30% x 3Dtruss, 50% x 3Dtruss, 30% x 3Dgyroid, and 50% x 3Dgyroid all show differences in compressive modulus of elasticity, compressive proportional limit, or maximum compressive stress results. Hence, despite a lack of statistical difference in the compressive proportional limit, based on the combined infill designs and infill densities, the results will be a difference in the compressive proportional limit.

To include examples of research that validates the findings of the current research, Brischetto et al. (2017, p. 13) yielded the following averages for their ABS specimens:

- Compressive modulus of elasticity of 805.1 N/mm²
- Compressive proportional limit of 28.49 N/mm²
- Maximum compressive stress of 37.51 N/mm²

Although their results are higher than those of the current study (see Figures 9 & 10), this is likely due to the internal nature of the specimens as Brischetto et al. (2017) tested 100% solid specimens.

The results of this study have demonstrated that the selected infill design and infill density will result in a significant amount of variation when they are changed by the technology management

professional. This illustrates the necessity of the technology management professional's ability to conduct research and develop strategies and plans to identify, develop, and implement innovative AM-based solutions.

The implications of these results are important to technology management professionals, and users of AM equipment for hobby, prototyping, production, or research. As previously discussed, one of the great advantages of AM is that users can easily change the infill density and infill design of parts to be produced. In the automotive and aerospace fields for instance, light weighting of parts is of great concern for fuel efficiency. Moreover, with the rise of more costly materials such as carbon fiber and metals, the choice of infill design and infill density can have a very pricy impact on the part to be produced.

Returning to the scenario in the introduction of an exoskeleton that is too heavy for a patient to even benefit from, consider the following study of an exoskeleton being designed and developed for an infant. Babik et al. (2016) tested the feasibility and effectiveness of an exoskeleton for improving the arm movements of an 8-month-old with arthrogryposis (a disorder where infants are born with significant muscle contractures and weakness across multiple joints). The exoskeleton that was used in the study was produced with AM equipment, using strong but lightweight polymer material, making it very helpful to the infant. Tools such as these can assist with play and movement in young infants during this very crucial developmental phase. Two crucial variables that a technology management professional must set for producing products, such as exoskeletons, on AM equipment are infill density and infill design. Hopefully, this study will be welcomed as a unique combination of infill designs, infill densities, and their effect on the compressive modulus of elasticity, compressive proportional limit, and maximum compressive stress of parts produced with NylonX polymer material.

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Design and Implementation of a PID-Controlled Heating System in a Virtual Reality Environment

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Abstract

In the industrial field, it is very important to have the ability to thoroughly understand the behavior and function of the systems that make up the production or control processes, since, by knowing the nature of the dependent and independent variables of said systems, it is easier It is the work of the staff dedicated to maintaining quality control over the processes. For this reason, during training of personnel on automation issues, not only digital control topics are taught, but also that the user can deal with dynamic systems that represent a more realistic behavior. In relation to this, the design and use of virtual systems for industrial training has been proven as a viable alternative when offering efficient and practical personnel training methods. The following work proposal contemplates the design and implementation of a dynamic process within a virtual reality environment, as well as the automatic control methodology used in the implementation of automation concepts. The main purpose is to model the thermal dynamic of a stirred tank, allowing the scenario to obtain and monitor the variables that affect the behavior of the system.

Keywords: dynamic systems, virtual reality, PID control, automation, industrial communication

Introduction

Industrial control systems (ICS) currently play a fundamental role in the development of factories and mass production systems at an international level, since they provide the ideal principles and methods for the development of operations that maintain a stable level of performance. Nowadays, it is difficult to find a system that does not contain some type of control scheme. ICS manage various components, such as monitoring devices and software systems to manage operations and automate them as much as possible. They balance the many components required to operate an industrial environment, ensuring that these components work efficiently and in sync with each other.

Given this high demand need for ICS, the industry has put considerable investment in training and conformation of highly qualified personnel that could satisfy very specific requirements in terms of understanding not only the type and behavior of dynamic processes a certain company may have, but also the right set of actions and operations of ICS that can monitor and control the most important variables of these processes. For this reason, training activities have been considered a critical operation as well for a wide range of modern companies. Although it is true that several industries use creative and/or traditional measures to train various processes, it is understandable why induction is not as effective as they would like, given that normal and non-upgradable training methods are tedious, boring and do not impact the learner enough to retain the information desired.

Literature Review

The evolution and constant adaptation of ICS has reached an important turning point in the last 10 years. This is due to the integration of automated processes and equipment, which are responsible

for carrying out programmed repetitive actions with greater efficiency than manual work (Huerta-Torruco, Hernández-Uribe, Cárdenas-Robledo, & Rodríguez-Olivares, 2022).

Automation through an industrial control system (ICS) has several advantages for industrial organizations. These systems allow to reduce manual operations and energy use, making better use of operational hours (Togias, Michalos, Makris, Gkournelos, & Angelakis, 2021). One positive effect of this implementation is the reduction of costs, which allows a company's production gauge to increase and improve, as well as increasing its profit margins, simplify staffing requirements, and reducing the price of operations (Guo, et al., 2020).

Virtual reality has been a great contributor in operational excellence for the training processes of today's companies (Bellalouna, 2020). As a result of the rapid popularity and flexibility of the design and implementation of VR scenarios, many software developers have taken the advantage of the tools provided by the game engines used to build these environments and have incorporated a wide range of toolboxes (Dammacco, Carli, Lazazzera, Fiorentino, & Dotoli, 2022).

Regarding the use of VR in manufacturing, many have been pushed to incorporate a high number of technological elements into the requirements needed for implementation in industry (Monetti, de Giorgio, Yu, Maffei, & Romero, 2022). By assessing requirements like efficiency and safety, designers can propose virtual layouts that include estimations of operation time, viability of a specific optimization course, test finished elements in a safe environment before they get released, and within recent times, expand the limit over what type of dynamic systems can be modelled virtually to understand its real-life behavior (Roldán, Crespo, Martín-Barrio, Peña-Tapia, & Barrientos, 2019).

Problem description

The main objective of this project consisted of the design and implementation of a controlled system into a virtual reality environment, based on the model of a heating system, and that it could incorporate as much real-life, ready for industry equipment as possible. One of the first steps in the realization was to identify the main problem that the project had to assess and the effect the solution of this project could have in a similar real scenario.

Although there is extensive documentation on the virtualization of digital processes in virtual environments, there is yet an opportunity area to exploit the potential of these tools to incorporate more robust and capable virtual systems that not only consider simple action-and-reaction events, but also systems with dynamic behaviors that deals with stability and efficiency requirements in their real-life counterparts.

For the purposes of this project, the proposed solution consists of the design and implementation of a dynamic process inside a virtual environment. Given the great variety of industrial applications that involve processes with complex system dynamics, it was necessary to consider a global example that could be used for most of these cases, in order to present a useful case study both in the academic and professional fields. The chosen case study deals with a heating tank system in which the desirable controlled variable is the temperature inside of the tank.

Methodology

By definition, the proposed model for the heating tank is described as a first order system, in which there's an incoming liquid (water) flow and temperature that is sent to a tank with a predetermined volume. The tank incorporates elements such as a temperature (TC) and level sensors, as well as a heat-providing element (Q). It is also important to consider the system to start at a steady state,

that the heat supplied to the system, Q, remains constant, and it is desired to know how the temperature of the outlet stream responds to this change.

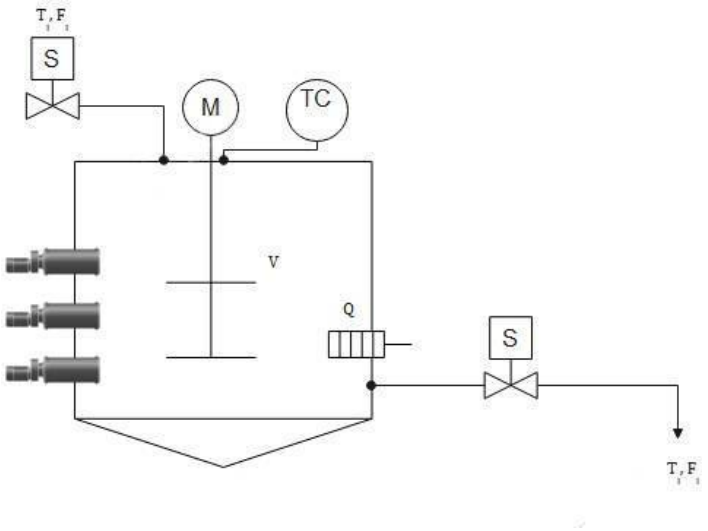


Figure 1. Diagram of the proposed tank-heating system.

After establishing the variables that are present in the system, the transfer function is to be developed by setting up the heat & material balance equations, considering a constant volume V:

$$\frac{dT}{dt} = \frac{F}{V}(T_1 - T) + \frac{Q}{\rho V C_p}$$

Where T_1 is the outcoming temperature from the system, and C_v corresponds to the specific heat capacity from the liquid (1 kcal/kg ^{o}C for water). According to stationary state, $T(0) = T$ and $T = T - T_s$.

$$\frac{d\bar{T}}{dt} + \frac{F}{V}\bar{T} = \frac{\bar{Q}}{\rho V C_p}$$

Rearranging terms:

$\frac{V}{F}\frac{d\bar{T}}{dt} + \bar{T} = \frac{\bar{Q}}{\rho F C_p}$, which mirrors $\tau\frac{dy}{dt} + y = ku$, where $\tau = V/F$ and $k = \frac{1}{F\rho C_p}$.

Finally, terms become:

$$\tau\frac{d\bar{T}}{dt} + \bar{T} = \bar{k}\bar{Q}$$

Applying Laplace:

$$T(s) = \frac{k}{\tau_s + 1}Q(s)$$

After the obtention of the transfer function of the system, the challenge comes in adapting this behavior to the simulation of the virtual environment. To achieve this, the bilinear transform method (or Tustin Method) was used. This is due to the fact that the system can adapt to a linear and invariant filter in the discrete domain. The z-transform is considered to correspond to the Laplace transform on a discrete function:

$$z = e^{sT} \approx \frac{1 + sT/2}{1 - sT/2}$$

Where T corresponds to the numerical integration or the sampling period. Inverse mapping allows for:

$$s = \frac{2}{T}\frac{1 - z^{-1}}{1 + z^{-1}}$$

Applying this concept to the system, the discrete-transform obtained is:

$$T(z) = \frac{Q(z)T_sK + Q(z-1)T_sK + T(z-1)2\tau - T(K-1)T_s}{T_s + 2\tau}$$

T_s = sampling time

Lastly, it became necessary to determine the controller for the system, which given the nature of the controlled variable (temperature), allowed the use of a PID controller, whose behavior is defined by the following equation:

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt}$$

And its discrete model (that the PLC block uses for this case study) becomes:

$$C(z) = K_p + \frac{K_i T_s z}{z-1} + \frac{K_d N(z-1)}{(1+NT_s)z-1}$$

After the obtention of the discrete-time equations, the implementation stage began. For this, it was necessary to represent with the upmost fidelity the virtual objects needed for the environment. The way in which this was accomplished relied on the design and editing of 3D objects that were imported inside Unity 3D, which is the game engine chosen for the development of this project. Within the design of the VR environment, it is important to consider the inclusion of the variables that serve as the link between the scenario and the controller. For this, a script based on C# language was written, in which the communication method is described.

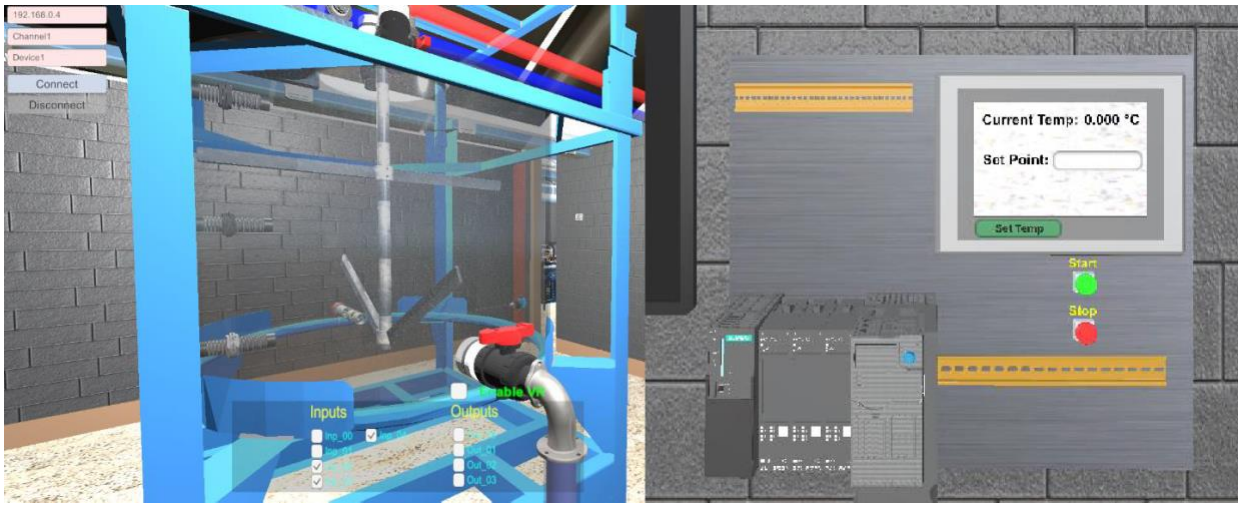


Figure 2. Virtual environment layout of the tank-heating system.

One of the most critical aspects of this proposal, as it was established before, is the inclusion of real-life controllers, with the purpose of adapting the VR environment to a friendly-like implementation for industry. For the purpose of this study, the selected type of controller was an Micro800 PLC from the Allen-Bradley® family, alongside the Connected Components Workbench® software. The main advantage of this software's use relies on its feature to create user-defined function blocks (UDFB), which allowed the scripting of the auto tuning routine for the PID controller.

The last crucial element of the system is the communication scheme that will support both the VR scenario and the PLC's input and output management, as well as the mirroring process for each other´s tags. To accomplish this, it was opted to make use of the Kepware® platform, which allows to implement OPC industrial protocols to link industry-ready devices and upload data to cloud storage. The VR environment connects to the OPC platform requesting and sending packages of data through the JSON format, and in exchange the OPC allows client-level access to the data

located inside an IoT endpoint, allowing the request to be processed by the OPC protocol back into the PLC, thus successfully manipulating the internal data inside the controller.

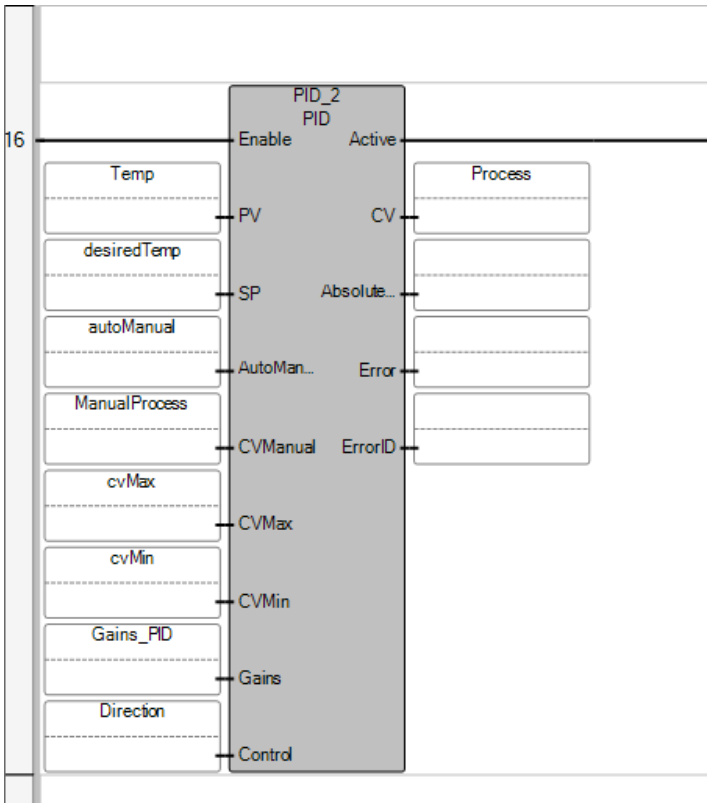


Figure 3. PID controller block for the programmable controller.

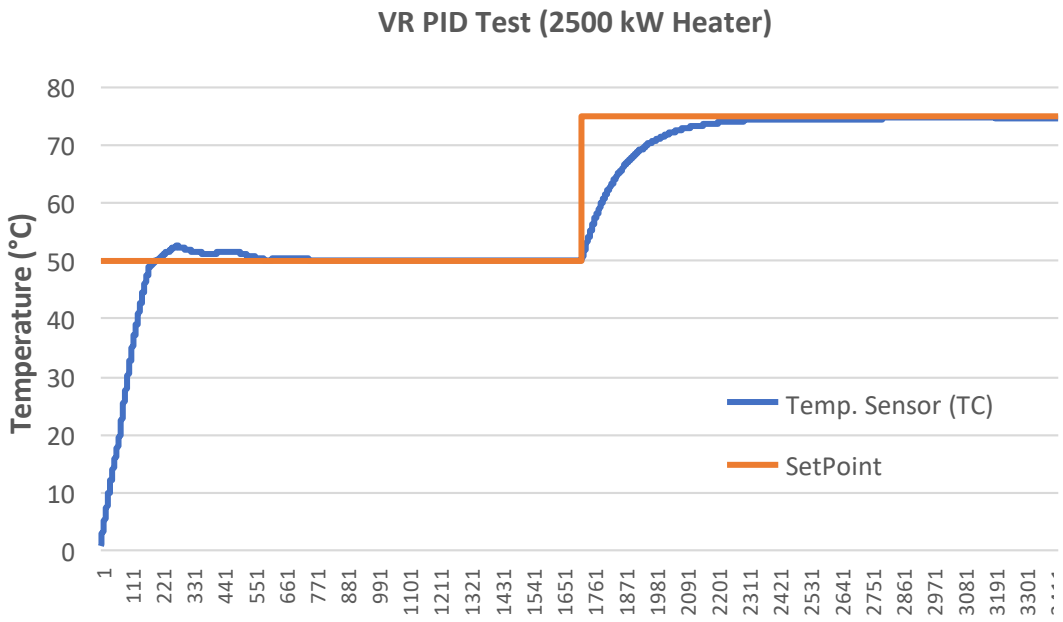
Item ID	Data Type	Value	Timestamp	Qualit
Channel2.Device2.Inp_00	Boolean	0	10:36:58.241	Good
Channel2.Device2.Inp_01	Boolean	0	10:36:58.303	Good
Channel2.Device2.Inp_02	Boolean	0	10:36:58.395	Good
Channel2.Device2.Inp_03	Boolean	0	10:36:58.678	Good
Channel2.Device2.Inp_04	Boolean	0	10:36:58.738	Good
Channel2.Device2.Inp_05	Boolean	0	10:36:58.784	Good
Channel2.Device2.Inp_06	Float	0	10:36:58.845	Good
Channel2.Device2.Inp_07	Float	0	10:36:58.149	Good
Channel2.Device2.Out_00	Boolean	0	10:36:58.952	Good
Channel2.Device2.Out_01	Boolean	0	10:36:59.045	Good
Channel2.Device2.Out_02	Boolean	0	10:36:59.090	Good
Channel2.Device2.Out_03	Boolean	0	10:36:59.138	Good
Channel2.Device2.Out_04	Boolean	0	10:36:59.230	Good
Channel2.Device2.Out_05	Long	2600	10:36:59.276	Good
Channel2.Device2.Out_06	Long	65535	10:36:59.367	Good

Figure 4. IoT endpoint server with the mirrored PLC/VR environment I/O tags.

Results and Limitations

Once the VR scenario layout was finished, the testing stage focused in running the programmed PLC routine to verify coherence of the system steps, and making sure the data manipulation between the controller and the virtual objects became clear for the user. One way in which this was accomplished on the graphics level was the implementation of a UI board that includes the inputs and outputs that correspond to the acting elements of the VR scenario. With this manual manipulation, a considerable part of the troubleshooting process was met successfully.

The main positive takeaway from the testing stage was observed when analyzing the data from the performance of the PID controller through the monitoring of the VR sensor, which contained the process temperature's lecture. When exporting the data, it can be observed that the proportional gain allows the system to obtain stability when reaching the first setpoint value. The introduction of a change in the setpoint value results in an acceptable removal of the residual error thanks to the integral term of the controller. In a similar way, the response time observed between the manipulation and control of the incoming temperature data stored in the IoT endpoint obtained good performance levels, in part thanks to the existing IT infrastructure.



Sampling Time (s)

Figure 5. PID controller performance through observation of monitored sensor temperature (*T*).

Although the proposal calls for the development of a scenario that can include features that can enhance the comprehension and manipulation of the virtual elements, one considerable limitation is the necessary work details that still need to be addressed, especially in terms of displaying the process information in such a way that the user can employ it for industrial applications, like condition-based maintenance, monitoring tasks, among others.

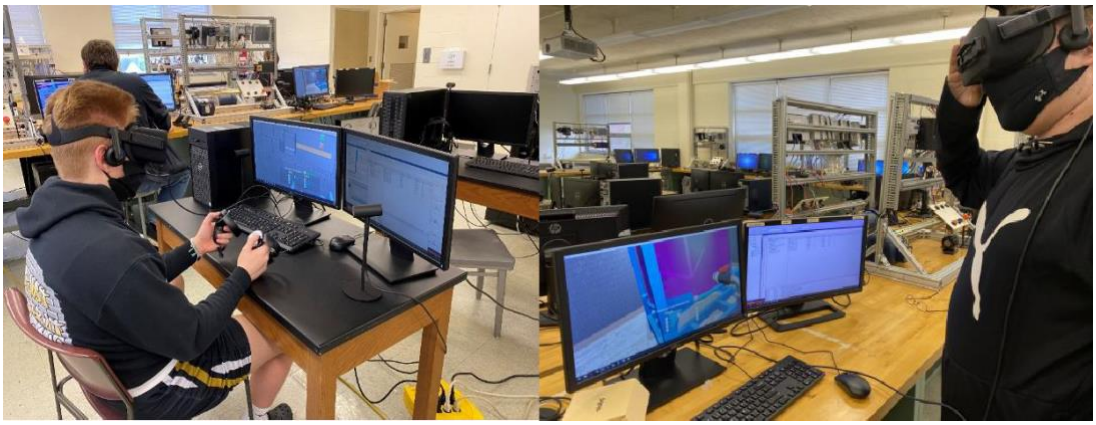


Figure 6. System being implemented in academic Automation courses

Conclusion

The purpose of this research was focused on developing a novel way of approaching users to a realistic experience that could offer them the same knowledge in manipulating systems that involved a more elaborated control scheme, considering the type of variables involved. By breaking down the development process, a wider and clearer comprehension of first-order system alongside the practice of virtual commissioning could be achieved, removing the hardware unfamiliarity gap that many people have with industrial systems.

Still, the proposed system has a wide utility for training users that already have some familiarity with a real-life process that involves a case study such as the one described in this proposal. The resulting test proved successfully the implementation of a communication process in which signals from a safety-controlled environment (in this case, done so virtually) can interact with automation control equipment that a significant number of companies make daily use nowadays, allowing this proposal to keep up with current technological development.

As a final note, this research can greatly benefit by considering the technological migration of this environment onto an AR environment, considering the use of real-time data obtained by running the physical process alongside its virtual counterpart. By doing this, future users can compare performance and data values between the two systems in order to bring a more synergic environment.

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Developing a holistic master's program in industrial technology focused on data and Industry 4.0

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Abstract

There are numerous masters programs available today nationwide in Industrial Technology. Some programs focus on Industrial Management, whereas some focus on lean manufacturing and supply chain management. Hence, there is a need to develop a program that fulfills the needs of Industry today with advanced topics like data analysis and smart manufacturing. In near future, Industries will demand a newly hired Industrial Technology student to possess skills beyond traditional manufacturing and management skills. These skills will tend towards data analysis and smart manufacturing.

Here we have proposed a novel program structure for a 30 credit hour Master's degree in Industrial Technology. This degree will cover 10 classes: Leadership skills, Continuous Improvement, Data driven decision making, Project management for Industry, Smart Manufacturing/Industry 4.0, Technology in the 21st century, Supply chain and operations management, Manufacturing production systems, Strategic and Entrepreneurial management, Advanced lean six sigma black belt techniques. These classes will cover in-depth knowledge on multiple facets of the Industry and will enable students with skills required for majority of managerial positions nationwide in various industries. Since this degree will be offered completely online, we have further discussed the issues and challenges of teaching these classes effectively via distance mode to satisfy the student learning outcomes.

Keywords: Master's program, Industrial Technology, Data, Smart Manufacturing.

Introduction

Today, a Bachelor of Science degree in Industrial Technology at Mississippi State University is a well sought after degree by students from diverse fields of study. This growing popularity of the Industrial Technology program is a result of growing student enrollment/ count and high job placement rate of about 94% after graduation. Many graduates are placed in renowned companies and the fact that this program is flourishing, encouraged us to plan for a new graduate master's degree. This graduate program in Industrial Technology needs to be holistic and updated, with classes based on current industry trends and advanced manufacturing skills. Also, this new program should provide students with knowledge on Data and future factories which will be based on Cyber physical systems (CPS) that involve integration of sensing, computation, control and networking into physical objects and infrastructure, connecting them to the Internet and to each other.

Literature Review

Traditional Graduate Technical Education

In 1990, the National Center on Education and the Economy's Commission on the Skills of the American Workforce stated that U.S. companies are facing the challenge of improving their productivity and quality of the products, they further reported that "if productivity continues to falter, we can expect one of two futures. Either the top 30% of our population will grow wealthier while the bottom 70% becomes progressively poorer or we all slide into relative poverty together." (Wilson, 1992). Concerned with the impact that this declining economy would

have on average Americans, Wilson (1992) stated that "held back by sluggish growth, our standard of living, which stood far above the level of Western Europe and Japan in the 1950's, was barely holding its own by the mid 1980's."

In response to the growing concern about the lag in the United States behind other developed nations in economic development, in 1988, Morrison, McGuire and Clarke surveyed 2300 senior researchers, 500 University leaders and senior state government officials in 50 states and the results indicated that “developing and maintaining adequate supply of science, engineering and technical personnel was viewed as the most critical issue to the competitiveness of the U.S. economy" (Morrison et al., 1988, p. 2). In addition, majority of respondents believed that postsecondary institutions are capable of finding solutions to problems confronting the national economy.

To help the U. S. economy remain competitive, colleges and universities must provide a workforce equipped with advanced technical skills and managerial knowledge required for functioning in U.S. technology intensive corporations (Morrison et al., 1988).

To make informed and intelligent decisions, corporate managers must be able to understand technology and analyze technological information because businesses are increasingly being driven by technology and managers have to understand the dynamics of technology and its impacts on the individual, society, and economy (Drucker, 1981).

In a survey conducted at BGSU (Bowling Green State University) in 1995, when their master’s in industrial technology program was launched, a team of 6 individuals developed a questionnaire regarding what technical content is important for this master’s program in manufacturing. This questionnaire was based on a 6-point Likert type scale and was mailed to all

SME officers in the Ohio valley region. The results of this survey indicated the following topics as very important: Total Quality Management, computer aided manufacturing, Quality and reliability testing, Study of the planning of industrial organizations, Development of research skills, Study of Data analysis techniques, computer aided design and study of just-in-time manufacturing. (Zargari et al., 1995)

Because technological methods and techniques for producing goods and services are continually changing, the required skills for individuals employed by service and manufacturing industries are also changing. Skills and knowledge required in industries today and in near future will vary greatly and tend towards what is referred to as the Fourth Industrial revolution.

Technical Graduate Education for the Future: Establishing the Competencies for interdisciplinary program

Today, industry is being driven towards fourth industrial revolution which is also referred to as The Digital Revolution or Industry 4.0. The Fourth Industrial Revolution is a term created by Klaus Schwab and defines a world where individuals move between digital domains and offline reality with the usage of connected technology to assist and manage their lives. The Fourth Industrial Revolution is the outcome of advanced technology, globalization of the economy, expansion of education, legislation, tradition and human relations.

The Fourth Industrial Revolution (4IR) focuses greatly on enhancing productivity in manufacturing and production systems through strengthening the relationship between digital, biological and physical worlds resulting in a great impact to all the industries and economies, as well as posing a threat to what it means to be human (Schwab, 2016). According to Schwab (2016), the nine pillars of the 4IR has been identified as big data and analytics, augmented

reality, simulation, Internet of Things (IoT), cloud computing, cyber security, systems integration, additive manufacturing and autonomous systems. In future the fate of industries and the economy, rests within the above-mentioned pillars and each of the pillars will impact life in general.

The Technical graduate education for the future will be based on these nine pillars of the Fourth Industrial revolution.

Discussion

Acquiring the Competencies for Interdisciplinary program

In view of these advancements the technical graduate education for the future will tend towards technological skills based on topics such as data science, business analytics, smart manufacturing, systems integration, predictive maintenance to name a few, along with the traditional manufacturing knowledge of production control and lean six sigma. Since the technical graduate education for the future will prominently train managers to empower U.S. technology intensive corporations, some management skills like leadership skills, supply chain and operations, strategic management need to be incorporated. Thus an Interdisciplinary technical graduate education program with focus on smart manufacturing, business and marketing management principles and core manufacturing principles of production control and lean six sigma will give a holistic Master's program in Industrial Technology.

In addition, to working with potential students from industry, this degree program is also intended for community college instructors. A core understanding of both data and CPS will enable them to better understand the issues that industry faces and help them to prepare students with the knowledge, at the associate's level, to be able to go into the workforce with a minimal

amount of on-the-job training. This 18-hour core when combined with 12-hours of community college leadership courses would make for a potentially high-level community college instructor with the ability for advancement in their field. These individuals will gain knowledge on current industry trends of advanced manufacturing. A community college instructor or a high school teacher experienced in these advanced technical concepts will foster this knowledge into high school and community college students, thus educating them on current industry trends. This process in turn will help many high school and community college students make better and informed career decisions and could also attract many students towards our Industrial Technology program.

Table 1.1 shows the program structure for a 30 credit hour master's in Industrial Technology, manufacturing concentration. For us to be able to deliver this interdisciplinary program we have a collaboration with the College of Business at Mississippi State University. We have incorporated 3 classes from the College of Business of which 2 are from the department of Business management and 1 from Marketing Management. These 3 classes Leadership skills, Supply chain and operations management and Strategic and entrepreneurial management will bring in the required expertise from the college of business into this program.

Table 1.2 shows the proposed curriculum for a 30 credit hour master's program in Industrial Technology, community college Leadership concentration. The 12-hours of community college leadership courses namely Community college finance, program planning and development, HR human resources, Teaching and learning will provide students in this concentration with a thorough knowledge on Community College Leadership.

Table 1.1

Masters in Industrial Technology	30 credit hours	Prerequisite
	CORE	
MGT 8113	Leadership Skills	
INDT 8123	Continuous Improvement	
INDT 8143	Data Driven Decision Making	
INDT 8153	Project Management for Industry	
INDT 8183	Industry 4.0 / Smart Manufacturing	
INDT 8223	Technology in the 21st Century	INDT 8183
	Manufacturing	
MKT 8213	Supply Chain and Operations Management	
INDT 8263	Manufacturing Production Control	INDT 8153
MGT 8103	Strategic and Entrepreneurial Management	
INDT 8243	Advanced Lean Six Sigma Black Belt techniques	INDT 8123

Table 1.2

Masters in Industrial Technology	30 credit hours	Prerequisite

	CORE	
MGT 8113	Leadership Skills	
INDT 8123	Continuous Improvement	
INDT 8143	Data Driven Decision Making	
INDT 8153	Project Management for Industry	
INDT 8183	Industry 4.0 / Smart Manufacturing	
INDT 8223	Technology in the 21st Century	INDT 8183
	Community College Leadership	
CCL 8123	Community College Finance	
CCL 8143	Program Planning and Development	
CCL 8153	HR Human Resources	
CCL 8173	Teaching and Learning	

Mentorship for Building Interdisciplinary Competencies

Mentoring of the students will be critical for their success in either industry or post-secondary education. To this end we envisage having both industrial and community college leaders to both come in and talk to the students about the challenges they face, and how they overcame them, as well as using these speakers as a resource to help individual students navigate their potential career path while undertaking the degree requirements. This form of mentorship would be

beneficial to both parties for the students they will get real-world insight as to how things work while the industrial/post-secondary mentors will strengthen their leadership skills through their mentoring of the students.

Traditional versus online Master's degree

Industrial Technology is traditionally an experiential learning program where students learn mostly through hands on training. It's a challenge to deliver this technology intensive program effectively through distance/online mode. The Bachelors program in Industrial Technology at Mississippi State University is delivered via both face to face and distance modes. Though we already see the difference in student learning outcomes between face to face and distance program. This difference is mitigated by the fact that our distance campus students are already working in the industry and have at least a couple of years of industrial experience. This experience at times puts the distance campus students at advantage and ahead of the traditional face to face students in overall learning experience.

Our Master's in Industrial Technology program is designed for students who are already in the Industry and who are looking to upgrade their skills and education for promotions in their jobs. On the other hand, a fresher with a undergraduate degree could also join the program and complete it with equal ease. We expect most of our students for this master's program to come with prior industrial experiences, this information is based off of regular talks we have had with our Industrial Technology alumni. The fact that most of our students enrolling in our master's program will have prior industrial experiences, makes us certain that we should be able to deliver this program effectively through distance learning mode.

Conclusion

Since the development of Master's degree in Industrial Technology at BGSU in 1995, there has been a tremendous advancement in technology. The interdisciplinary skills and knowledge required for todays and future Industrial Technology graduates is a blend of marketing management skills and leans strongly towards smart manufacturing. This 30 credit hour Master's program in Industrial Technology at Mississippi State University will build advanced manufacturing skills and enable future leaders in technology to better equip themselves to serve the needs of America's modern age industries. Similarly, Community College Leaders will gain knowledge that will not only assist them in their careers but also help them transform students from secondary and post-secondary education into future Industrial Technologists

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Engineering Technology Undergraduates Assisting Civil Engineering Research through Automation

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[1]Murray State University, [2] Murray State University, [3]Murray State University

Abstract

This paper looks at an example of how engineering technology undergraduate students in the Electromechanical Engineering Technology program at Murray State University utilized their background in automation to assist in fundamental civil engineering research. The authors developed a large climatic chamber to study the interplay between varying environmental conditions and fundamental soil behavior. Undergraduate engineering technology students assisted in the installation and testing of automated systems to monitor and control temperature and relative humidity within the chamber. The Murray State University students utilized sensors, an Arduino system, and programmable logical controllers to log and trend data to assist in the research. The paper discusses best practices of utilizing applied engineering students to assist in theoretical engineering research.

Introduction

Both traditional engineering and engineering technology have strengths that both disciplines can collaborate with to complete research projects. While traditional engineering curricula tend to focus on theory, higher level mathematics, and research, engineering technology (ET) programs tend to focus more on applications, especially industrial applications. Some universities have barriers between the field of studies, but this is generally not found in

industry as both engineering and ET graduates utilize their strengths as a team in their professions to accomplish goals.

Successful research that encompasses both disciplines can occur between faculty and students in both engineering and ET. This paper will look at one such example of this occurred recently at Murray State University when an instructor, and a PhD student from Murray State University utilized an ET student to further automate his research to make it more flexible. Murray State University has ABET accredited engineering programs and several ET programs under their School of Engineering. The coauthor involved in research in numerically modeling soil failures teamed up another faculty member in an ET program to add flexibility to his research with increased automation. The university also houses an automation engineering program called Electromechanical Engineering Technology (EMT), so the faculty of both programs partnered to allow EMT students to assist in the civil engineering research, which not only benefitted the research outcomes but also the EMT faculty, and EMT students that were involved since research can be harder to achieve in an applied engineering program. The EMT student also received experiences in developing an actual system to accomplish a task, which gave them real world experiences. This paper will look more specifically of how the EMT student utilized applied automated systems to meet the needs of the research.

Background

The number of ET programs are declining in recent years in the United States. In 2014, the number of four-year ET graduates were 17,915, while there were 93,950 engineering graduates in that same year (Bridge, 2017). It is believed that much of this was due to university research policies for faculty and declining college budgets. ET seemed to rebound immensely from 2015-2019, as graduates of programs in Industrial/Manufacturing Technology and

Architecture Engineering Technology grew over 300% with each program (Stuppard, 2020). The correlation of the ET programs growth is unknown, but the growth can present problems in research or comprehensive universities. One of the issues is the fact that many universities have tenure and promotion policies that do not welcome faculty members with ET backgrounds. Currently, there are very few universities that offer PhD's in ET programs (Hildebrant et al., 2018). This presents a problem with ET graduates becoming faculty in similar programs that they graduated from. This hurdle could be overcome by universities accepting ET graduates with master's degrees and industrial experience in lieu of a PhD. Another challenge that this can present is that the faculty must accomplish research to accomplish policies set forth for tenure and promotion (Hildebrant et al., 2018). One way to accomplish this is having ET faculty partner with engineering faculty for research purposes, and since ET graduates generally become engineers in industry (Land, 2012), partnering with engineering faculty and engineering students are also good practices for their professional careers. This also breaks down negative perceptions of the different programs by exposing faculty and students of both disciplines to each other and building on their strengths. This is extremely beneficial for regional universities that do not have engineering master's degree programs.

Automation Curriculum

The EMT program at Murray State University focuses heavily on automation and controls utilized in manufacturing processes. Students take courses in electrical circuits (I and II), motor controls, and electrical distribution for the electrical competencies, then they complete fluid power, statics and strengths of materials, and dynamics for the mechanical competencies. Once both foundations are built, the students take four courses associated with programmable logical controllers (PLCs): Basic PLC programming, Industrial Instrumentation with analog PLC

programming, Industrial Networking with HMI programming, remote input and outputs, and advanced PLC programming, and a robotics and motion controls course that include a Fanuc certification and integrating variable frequency drives, and hydro-electric systems. In addition to these courses, students also complete a course on Supervisory Control and Data Acquisition (SCADA) systems and a senior design course where students design and build automation systems. The project in this paper utilizes the senior design class, but work begins the semester before the student take the senior design course.

Methodology

The research conducted by the coauthor required the construction of an environmental chamber capable of supporting large soil samples (Figure 1). The exterior structure of the environmental chamber consists of a 40 mm extruded aluminum frame and hardwood plywood exterior (Figure 1a) for stiffness.

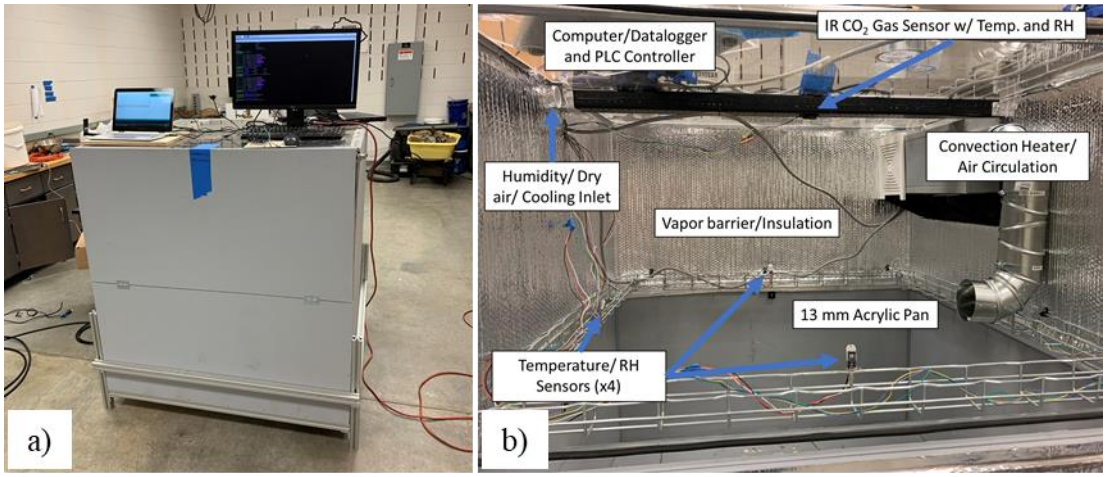

Figure 1. (a)Exterior and (b) interior photographs of the environmental chamber.

The interior of the chamber consists of a 13 mm acrylic pan on the bottom 60 cm, and reflective insulation around the top of the chamber's interior to serve as a vapor barrier and

improve the thermal efficiency of the chamber (Figure 1b). The interior is sealed with clear silicone and aluminum tape. The top of the chamber is 13 mm acrylic sheeting. Figure 2b shows the interior configuration of the climatic chamber. The chamber has internal dimensions of 116 cm x 116 cm x 120 cm (L x W x H) and is designed to work with temperature and humidity ranges of 20-50 °C and 15-60%, respectively. The acrylic pan inside the chamber accommodates samples up to 60 cm thick.

The Arduino Uno Rev3 was chosen to serve as the controller and data collector for this project. The Arduino was chosen due to the ease with which it connects to the temperature, humidity, and CO2 sensors which were required by the nature of the project. Specifically, the combination of the Arduino being 5V, which matched with the sensors, avoided use of costly voltage converters that have the potential of changing the incoming data. In addition, there are many premade libraries which allow for a swift setup of sensors when using an Arduino based system. Arduino is an open-source microcontroller board with built-in software and an integrated development environment (IDE), which makes it easy to modify and upload code for various types of projects, control various outputs, and manage data from various inputs. The Arduino Uno board has the ATmega328P microcontroller chip, 20 input/ output pins (14 digital inputs/outputs, 6 analog inputs), a 16 MHz CPU, USB connection, power jack, an ICSP header, and a reset button (Arduino, 2022). When connected by the USB connection on a PC, it is easy to read and print the serial data from the sensors (or other devices controlled by the input/ output pins) and save the data as a CSV or text file with the PC's timestamp. This feature can be extended to view data live as it comes into excel allowing the user to see data trends live (Arduino, 2022).

The basis of the circuit constructed was using a series of relays connected to 5V outputs on the Arduino to control 120VAC outlets. The relay controlled 120VAC outlets then powered a series of fans, a heater, and a humidifier. These relays were controlled by logic written in the Arduino IDE coding language, a subset of C++. The 5V humidity temperature, and CO2 sensors acted as the inputs going into the various analog and digital pins on the Arduino. Existing libraries allowed for easy adaptation of the example sketches, the name for Arduino programs, to allow for quick modifications to the code and the parameter set points.

Results and Lessons Learned

To test the functionality of the temperature control, a series of tests with varying temperature and constant relative humidity were run. The chamber was tested at RH = 25% and target temperatures of 35, 40, and 45 °C for approximately 2 hours each. The results of the temperature control tests are shown in Figure 2. For each of the tests shown in Figure 2, the target temperature is shown beside the curve. The temperature generally oscillates about the target by a maximum of ± 1.2 °C.

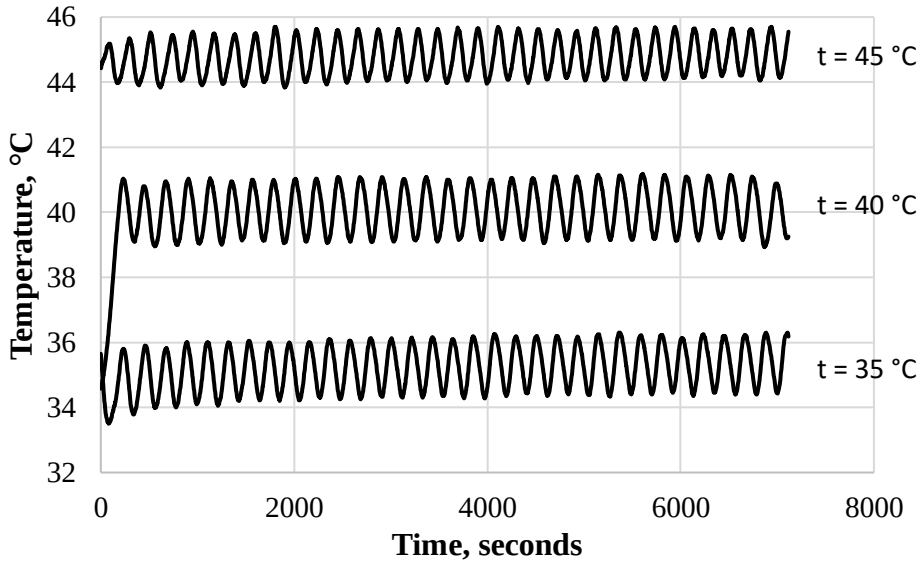

Figure 2. Test of the environmental chamber temperature control at 25 % relative humidity.

The temperature in the chamber is generated by a custom-designed forced-air heater that is located within the chamber. The heater runs on 1350 Watts of power and outputs a volumetric flow of 1.4 m^3/min. The heater is controlled by a proportional-only algorithm where the unit is either on at full power or off, depending on whether or not the temperature has reached its set point. When the heater is off, the temperature slowly dissipates, falls below the setpoint, and is turned on again at full power. This method of controlling temperature provides good results, but the energy efficiency and temperature oscillation could be improved using a proportional–integral–derivative (PID) control system where the power is regulated based on the difference between the setpoint and the actual temperature in the chamber.

Humidity is controlled in the environmental chamber using the same algorithm as the temperature control and is provided by means of an off-the-shelf ultrasonic humidifier. The ultrasonic humidifier produces a room temperature mist by vibrating a small metal diaphragm in water at a high frequency. The results of varying humidity are shown in Figure 3. which

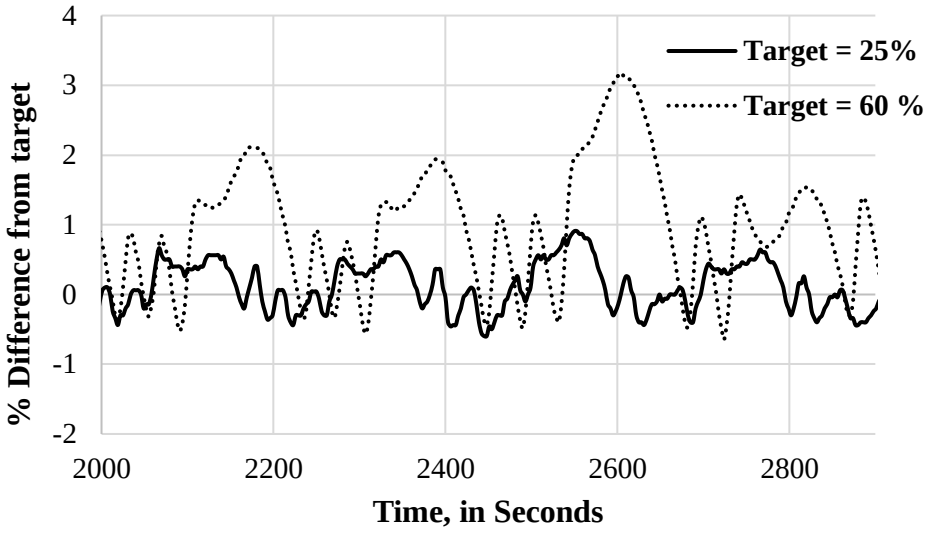

Figure 3. Test of the environmental chamber humidity control at 35°C.

shows the results for two target relative humidity values of 25% and 60 %, respectively. The tests ran for approximately 2 hours, but the graph in Figure 3 shows the percentage difference between the target relative humidity and the actual relative humidity for a 15-minute time frame. The results show that the lower humidity level is much more stable and varies less than $\pm$ 1 %, but the humidity level at 60 % usually varies around $\pm$ 3%, which are reasonable oscillations for tests on soils.

The given solution was efficient but potentially flawed in that a variable DC power supply was used to provide supplemental 5V power to the various devices. A better solution may have been to purchase a dedicated supply for the 5V power. A protoboard was soldered to in order to wire the electronics, this made it difficult to adjust the wiring. A better solution could have been using various quick connects to allow for greater flexibility in the wiring. The wires were not all color coded due to supply constraints, this made troubleshooting difficult on occasion. Having the data only being backed up to one device could potentially be dangerous if there were to be a loss of power or if the USB cord was disconnected. A solution would be to

store the data simultaneously to a local storage solution such as an SD card. There were more efficient ways to display the live data about temperature, humidity, and CO2 within the chamber such as hosting a website which could be accessed remotely to check in on the trends within the chamber.

Conclusion

It is important for faculty at smaller regional institutions that are not supported with graduate programs to engage in research with undergraduate students. This paper demonstrates the utility of using undergraduate research assistants to assist faculty in cross-disciplinary research. Undergraduate students in Engineering Technology assisted in the design, programming, and installation of an automated control system for a climatic chamber that is geared toward civil engineering research. The design of the chamber in this study is a low-cost, fully automated, and fully customizable system capable of controlling environmental conditions with precision and accuracy. The faculty member completing the civil engineering research did not have to include the EMT student in their research, but by including the student, it gave the ET student the ability to participate in research that they would normally not be involved with, and it added flexibility to the control system utilized for research. Combining disciplines for research benefits both parties.

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Implementing a Leadership Matrix Framework for Technology Programs

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Introduction

"Leadership is the process by which an executive imaginatively directs guides and influences the work of others in attaining specified goals" (Alam et al., 2019). Furthermore, the concept of educational leadership is to observe administration's role in the influence of the school's organizational structure and strategy. School leaders are those people, occupying various roles in the school, who provide direction and exert influence in order to achieve the schools' goals and end objectives. However, evaluation of leadership in higher educational institutions has led to limited research knowledge as case studies have been few. This is very prevalent in technology programs.

One way of evaluating leadership is by the implementation of the Malcolm Baldridge Excellence Framework (MBEF). Though the MBEF covers seven different areas, this paper focuses on the "leadership" area of MBEF and creating a leadership framework to be used in the technology program at East Carolina University. By establishing a leadership framework built on quality standards and change management, technology programs will be able to evaluate how identified stakeholders in the organization communicate and create effective strategies to reach program goals to better prepare students for industry needs of today and tomorrow. This proposed framework will also help in closing an identified gap in lack of knowledge of higher education and leadership evaluation regarding technology institutes.

MBEF at a glance

MBEF was established and developed in the 1980's to lead businesses in organizational structure and productivity (Miranda & Reyes-Chua, 2021) and named after former U.S. Secretary of Commerce, Malcolm Baldridge (Ruben & Gigliotti, 2019). One noted advantage of MBEF is due to its broadness of methodologies in which it provides flexibility to enable consistency of quality and performance (Miranda & Reyes-Chua, 2021). This also allows MBEF to be implemented into varying industries that can range from manufacturing, educational, healthcare, nonprofit, and other sectors. MBEF encompasses seven categories that are as followed: leadership, strategic planning, customer focus, measurement/analysis/knowledge management, workforce focus, operation focus, and results (Ruben & Gigliotti, 2019). The focus of this paper revolves around the first element of MBEF, leadership (Ruben & Gigliotti, 2019).

The leadership category of MBEF focuses on how leaders and leadership within the organization encourage excellence and innovation of the program utilizing the varying stakeholders along with developing assessments for current leadership practices (Ruben & Gigliotti, 2019). Several studies have noted the importance of developing accurate assessment measurements for MBEF that all stakeholders, especially leaders, are willing to embrace to develop a continuous improvement plan (Alam et al., 2019; Ruben & Gigliotti, 2019). In MBEF the three main areas of leadership revolve around vision and values, communication, and mission and organizational performance (Alam et al., 2019).

Previous MBEF studies

During research for the proposed framework of this paper, several studies were noted to be of importance for either their use of MBEF or for views on MBEF. Beard & Humphrey

(2014) noted the impact of MBEF and developed a balanced scorecard for IT in higher education. It was during their research where they noted that all stakeholders from faculty to administration to outside stakeholders should all play an active role in the development of mission statements along with priorities of the university. Beard & Humphrey (2014) were also critical of how performance measuring metrics should be consistent with the institution's mission, objectives, and goals while relying on a multifaceted approach.

Like Beard & Humphrey (2014), Niewiesk and Garrity-Rokous (2021) also noted MBEF within the development of their leadership framework for academic administrative work. However, Niewiesk & Garrity-Rokous (2021) decided the basis for their framework would be based on behavioral model of leadership instead of MBEF due to the focus on people-related tasks. It is important to note that during their findings it seemed that contradictory attitudes existed between individuals in the institution and those from administration to those of faculty. Further, Niewiesk and Garrity-Rokous (2021) concluded an issue that may occur is leadership in institutions is often due to the recruitment from the faculty talent pool and a good faculty member may not translate over into being an effective administration leader.

The last study to note was by researchers Alam et al. (2019) who focused on leadership in principals by using MBEF standards. Continuously throughout their study Alam et al. (2019) described how effective leadership from the top can transform an educational institutions goals and strategy for the better. Using questions that touched on the three categories of leadership under MBEF Alam et al. (2019) distributed a survey to both principals and teachers in varying schools on what impact the principal should and does play on the institute. It was concluded that both respondent groups viewed the role of principal leadership extremely important in shaping culture. The study also concluded that MBEF is important to create standards among those in

schools and should continuously be used and reflected upon to maintain a positive relationship among employees.

Proposed framework

During research of MBEF it was observed that limited research existed in applying an MBEF framework specifically to universities with technology backgrounds. For the purposes of this paper, we have identified technology universities as those who have an emphasis on science, technology, engineering, and math (STEM) degrees. The proposed framework may be used in conjunction with other questions of MBEF for the researcher or institute to gain better insight into stakeholder feedback on the condition of the program. What separates this framework from others is the emphasis of questions regarding technology and the role of leadership in preparing faculty and students to meet the future needs of tomorrow's Industry 4.0 workforce.

Appendix A shows the proposed framework that would be distributed through a Qualtrics survey. Using a Likert Scale with a range of Strongly Agree (5) to Strongly Disagree (1) allows institutes to observe responses in a format that can be quantified for data analytics. Furthermore, the framework is broken down by respondent categories: Administration (chair, dean, chancellor), faculty, and stakeholders (advisory boards, industry partners, etc.). It is recommended that those who use the framework would record the average for each category in relation to the question that is asked. By using the average, it would allow institutes to draw inferences in similarities and differences between the varying respondent groups. The framework can be used as an addition to other surveys that may include such factors as demographic information, degree programs offered, and respondent category of one of the following: administration, faculty, stakeholder.

Questions on the framework are arranged in the order of MBEF leadership subcategories. Questions 1 & 2 are focused on respondents' belief that the program's current strategy aligns with the vision & mission statement of the college in the present as well as the future. Beard & Humphrey (2014) stressed in their research the importance of input from the faculty, administration, and stakeholders regarding the development and priority of the mission statement of the college. Though other questions do touch upon the second category of communication, question 2 is the only one within the framework that is explicit in asking the respondent to rate how effective communication is between administration and faculty.

The remaining questions of the framework heavily emphasize the last category of MBEF leadership, mission & organizational performance. Specifically, these questions are asking the respondent to reflect on how the college impacts both internal and external stakeholders, the drive for innovation, and the preparation of the college in meeting the current technical needs and encouraging faculty to prepare for future needs. Questions are also formulated to address the impact the college is having on different stakeholder levels which may be of importance due to college mission statements, such as the one at East Carolina University, state the plan for the college to be a leader in state, national and global areas of research. The specific address of the college interlinking with industry within the questions is something this framework offers that was not noted in previous literature by the researchers.

In theory, this framework would be distributed at the beginning of the college year to establish a baseline for administrators to use and formulate a strategy when areas of need are identified. Ideally, after the initial responses are garnered administration may distribute another survey or hold a "town hall" meeting with faculty and stakeholders to reflect on responses and gain better insight on particular areas. Identifying areas of concern early in the year would allow

administrators to adapt to what their current strategy is and possibly shift resources to address shortcomings from the framework feedback. Administration may also redistribute the framework during the winter break to establish another baseline to compare initial response and again readjust strategies and goals for the spring semester. Finally, it is recommended a third distribution of the survey to occur during the end of the spring semester to once again establish a baseline and comparison to prepare for the next academic year.

The importance of having multiple baselines serves several purposes. First, it addresses continuous improvement and assisting programs in making sure that goals are closely aligned during the academic year through quantifying data which is important (Beard & Humphrey, 2014). Secondly, because this is geared toward technology programs and technology is constantly in a state of change, it helps in creating a synergy among respondent groups to ensure the program is not being left behind and able to develop tomorrow's workforce within the student population.

Conclusion

Though MBEF has shown massive benefits in being implemented in a variety of organization types and within higher education, there are still ways to use it as a guideline to adapt in more specific terms. Further, since MBEF being tailored toward technology programs has at this point been extremely limited, the proposed framework helps in closing that knowledge gap. This framework only addresses one specific area, leadership, but in the future may be adapted toward the other areas of MBEF. At this time, the framework is to be used at the researchers' university as a pilot study to address the ability to replicate at other programs. It is critical that technology programs have effective leadership due to the area of constant change it entails. Failure to do so may impact the program in preparing students for the workforce and for

the program's ability to recruit potential students as well as issues between administration, faculty, and identified outside stakeholders.

Appendix A

No.	Likert Scale 1 to 5 (1 strongly disagree, 3 neutral, 5 strongly agree)	Administration	Faculty	Stakeholders
1	Our current college strategy closely aligns with the mission statement and vision statement			
2	Our college has clear strategy, goals, and objectives for future direction			
3	Our college has effective communication channels between leadership and faculty			
4	Our college leads faculty in the development of new processes for students to contribute to the workforce			
5	Our college's leadership encourages ongoing education for faculty to adapt to new industry needs			
6	Our college is developing new programs that will benefit tomorrow's workforce			
7	Our college is concerned about our student and faculty impact on the following levels a) Local b) State c) National d) International			
8	Our college encourages collaboration between a) Intercollege b) Outside college c) Industry			
9	Our college actively engages with industry partners to strengthen innovation			

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A Review of Commercialized Firefighting Robotics Technology

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Abstract

Forest fires and structural building fires can cause severe problems for our society, the environment, and the economy. Firefighters face high risks and hazards during fire suppression activities. According to the National Fire Protection Association statistics, 67% of the firefighter casualties were caused by overexertion/stress or rapid-fire progress or explosions. Early detection of fires, monitoring, and fire behavior modeling are the most critical factors to minimize the environmental impacts and the economic loss. An emerging method is using robotics technologies for firefighting to increase firefighter safety and to minimize the negative impact on the environment and the economy. This study is a review of the state-of-the-art firefighting robotics technologies. Twelve robots have been found in the literature and the media, which can be modified based up on customers' requirements. The humanoids, solely reconnaissance robots, and conceptual design prototypes are out of the scope of this paper. The study specifically focuses on commercialized ground robotics for fire suppression; their specifications, capabilities, limitations, and use cases. The major technical limitation is the restricted control range of around 300 m (984 ft), and an obstacle for fire departments is that currently the base models start at $200,000. Yet, the fact is that it is a onetime investment with particularly long useful lives, and most importantly these robots can help with saving firefighters' and victims' lives and lessen the time to control fires.

Keywords: Firefighting robotics, fire suppression robots, robotics for reconnaissance

Introduction

Structural building fires and wildfires can cause devastating consequences for our society, environment, and economy. According to the National Fire Protection association (NFPA), US fire departments respond to an average of 346,800 home structure fires per year, causing an average of 2,620 civilian fatalities, 11,070 major injuries, and around $7.3 billion direct property damage (Ahrens & Maheshwari, 2021). In 2021, there were 58,985 wildfires that burned over 7 million acres of land, causing suppression costs of around $4.4 billion (Ahrens & Maheshwari, 2021). During combating these fires, fire fighters face serious risks, such as heat exhaustion, burns, physical and mental stress, long-term work-related musculoskeletal disorders, and an increased likelihood of many diseases due to exposure to high levels of toxic gases, such as carbon monoxide. A National Institute for Occupational Safety and Health (NIOSH) study revealed that fire fighters have a high risk of cancer diagnosis and cancer-related death, mostly from digestive, oral, respiratory, and urinary cancers (CDC, 2018). To reduce the risks and hazards faced by fire fighters, and to combat wildfires and structural building fires more efficiently, there is an emerging need to increase the use of robotics for firefighting. Robotics, such as drones, have lately been used by over 69 fire departments across the U.S. (Gettinger, 2017), mainly for enhancing situational awareness by using thermal or infrared sensors. Bogue (2020) reviewed the use of firefighting robotics and concluded that the use of robotics was still at an early stage and that use cases could increase in the future with the ongoing advances in the technology, such as increased battery life, use of hybrid sources, and increased payload capacity of aerial robots.

This article reviews the state-of-the-art firefighting robotics technology in terms of their capabilities, limitations, use cases, and associated costs. The study does not include entirely the

same categories of specifications for each robot due to, in many cases, the lack of information provided by the manufacturers. Further, this study includes only ground robotics, since drone technology is still way behind in terms of their fire extinguisher supply capacity due to their payload limitations. Currently, drones are commercialized only for reconnaissance to enhance situational awareness, while fire-suppression drone designs are still at the conceptual stages. These conceptual designs include payload dropping or a spring gun mechanism using fire extinguishing balls (Aydin, 2019, Alshbatat, 2018, Manimaraboopathy, 2017, and Soliman, 2019), a water/foam sprayer (Viegas, 2022), or a combination of both (EHang 216 F: https://www.ehang.com/ehang216f/). Drones carrying a CO_2 extinguisher (Vyshnavi, 2017), inert gases (Sato, 2013), a blanket to drop over a fire (Walter, 2021), or elevating an attached fire hose have also been proposed in the literature. Even though there exists several animated or real-time marketing videos on social media that purport to show information on the efficiency of fire-suppression drone designs, these are somewhat misleading and none of these can truly suppress fires, except perhaps for a short grass fire at its earliest stage (Aydin, 2019). On the contrary, ground robotics have been demonstrated to be successful in fire-suppression activities, thanks to the possibility of their extensive payload capacity and the option for a direct connection to water sources with external fire-resistant hoses.

The section below covers the current commercialized, readily available robots, while the later section provides a discussion of the cost–benefit, limitations of the firefighting robotics, and further research direction. Solely reconnaissance robots and humanoids are out of the scope of this paper and not discussed.

Commercialized Fire-suppression Robots

A review of the literature and media sources revealed a total of twelve firefighting robots, with most of them proposed to aid in the following applications: fire suppression, inspection, transporting equipment, respiratory support, chemical, biological, radiological and nuclear (CBRN) sanitizing, evacuating victims, removing obstacles, and smoke and toxic gas extraction. Most manufacturers support customized options based on specific customer needs. All the robots are claimed to be waterproof, and can withstand extreme heat, thanks to the materials used and their cooling systems.

Among the robot systems found, Thermite RS1 and RS3 robots (Figure 1) are produced by US-based company Textron's Howe and Howe Technologies. Both robots can be remotely operated and are equipped with standard and thermal video systems.

Figure 1 Thermite RS1 and RS3. https://www.howeandhowe.com/civil/thermite

Table 1 Specifications comparison of the Thermite RS1 vs. Thermite RS3 systems

	Thermite RS1	**Thermite RS3**
Dimensions (inches) (Length, Width, Height)	77" × 44" × 64"	120" × 66" × 65"
Max Flow Rate	1,250 gpm	2,500 gpm
Engine	24 HP Diesel	36.8 HP Diesel

Winch	5,000 lb	8,000 lb
Standoff Range	0.3 miles	0.3 miles
Speed	6 mph	8 mph
Runtime	Up to 20 hours	Up to 20 hours
Max Slope	+50% Grade slope 35% Side slope	+50% Grade slope 35% Side slope

Each model must be connected to an external water source by fire hoses. Los Angeles fire department has been using the Thermite RS3 since 2020.

Another system is the MHI Water Cannon robot developed by Japanese firm Mitsubishi Heavy Industries (MHI), which is operated autonomously in conjunction with a hose extension robot (Figure 2). Based on the findings of ground and aerial reconnaissance robots, the water cannon and hose extension robots can travel autonomously at a maximum speed of 4.5 mph toward the fire location and discharge a water/foam mixture at a maximum flow rate of 1,507 gpm. The hose is extended and rewound automatically based on the movements of the water cannon robot. The hose extension robot can lay a heat resistant fire hose up to 300 m (984 ft). The robots are equipped with RTK-GPS, RIDAR, IMU, and odometry sensors onboard. The robot's dimensions are 85" by 57" by 81.4" (https://www.mhi.com/products/energy/firefighting_robot_system-news.html).

Figure 2 MHI Water Cannon Robot.

Estonia-based Milrem robotics offer the “Multiscope Rescue with Hydra”, and “Multiscope Rescue Post-fire” systems (Figure 3). The Multiscope Rescue with Hydra robot is designed to be used for industrial, warehouse, tunnel, and wildfire extinguishing, while the latter is designed specifically for post-fire hot-spot detection and extinguishing. Table 2 shows the specifications of each model. The hydra system is attached to an external water source with a hose, whereas the post-fire system has an onboard tank. Each model is offered with hybrid or fully battery powered options. (https://milremrobotics.com/).

Figure 3 Multiscope Rescue with Hydra and Rescue Post-fire Robot Models.

Table 2 Specifications comparison of the Milrem Multiscope model

	Multiscope Rescue with Hydra	Multiscope Rescue Post-fire
Dimensions (inches) (Length, Width, Height)	95" × 79" × 45"	95" × 79" × 45"
Max Flow Rate	792 gpm	158-gallon onboard tank
Engine	- Battery pack: lead acid or Li ion - Hybrid with diesel engine and electric generator	- Battery pack: lead acid or Li ion - Hybrid with diesel engine and electric generator
Winch	15,000 N	15,000 N
Standoff Range	0.93 miles	0.93 miles
Speed	12.4 mph	8 mph
Runtime	- Up to 1.5 hours on the battery - Up to 15 hours hybrid	- Up to 1.5 hours on the battery - Up to 15 hours hybrid
Max Slope	31 Degrees grade slope 17 Degrees side slope	30 Degrees grade slope
Water Disperse Distance	62 meters	62 meters

Shark Robotics, a French robotics developer, offer the Colossus fire-suppression robot (Figure 4). This robot was utilized in critical fire-suppression operations during the Notre Dame De Paris fire in 2019, as well as to tackle several tunnel, warehouse, agricultural, parking lot, and industrial fires. It includes a water/foam cannon with a maximum flow rate of 792 gpm. The water source is external, supplied by a connected hose. It comes with 6 Li-ion batteries, providing 12 hours of operation time. The control range is 0.62 miles, with three controller options: handheld, vehicle mounted, and smartphone/tablet application. The robot can speed up to 3.1 mph and can handle up to a 40 degrees grade slope and 35 degrees side slope. The pulling

capacity is 1 ton, with dimensions of 63" by 31" by 30” (https://www.shark-robotics.com/shark-robots#colossus).

Figure 4 The Colossus

Italian robotics company EmiControls and German firefighting equipment specialist Magirus have collaborated to produce the TAF 35, TAF 60, and TAF 60X firefighting robots (Figure 5). Super Vac is their US dealership.

Figure 5 EmiControls and Magirus’ TAF 35, TAF 60, and TAF 60X models

These robots have external nozzle rings that atomize water into a fine mist, and then distribute it using propellers to take advantage of the water mist effect, drawing heat from the fire very

quickly (https://www.emicontrols.com/en/fire-fighting/mobile-fire-protection/firefighting-robot-taf35). TAF models have been used in China and Australia to protect subways and electrical transformers and substations (Bogue, 2021). A comparison of the specifications of the TAF series is provided in Table 3. The difference between TAF 60 and TAF60X is that the head monitor can be controlled separately from the turbine, thus increasing the extinguishing area.

Table 3 Specifications comparison of the TAF model series

	TAF 35	**TAF 60**	**TAF 60X**
Dimensions (inches) (Length, Width, Height)	118" × 65" × 87"	122" × 65" × 79"	124" × 65" × 85"
Max Flow Rate	- Water mist, 396 gpm - Full jet, 1,241 gpm	- Water mist, 396 gpm - Full jet, 1,585 gpm	- Water mist, 396 gpm - Full jet, 1,585 gpm
Engine	71 HP Diesel	71 HP Diesel	71 HP Diesel
Winch			
Standoff Range	984 ft	984 ft	984 ft
Speed	9 kph (5.59 mph)	9 kph (5.59 mph)	9 kph (5.59 mph)
Runtime	N/A	N/A	- N/A
Max Slope	30 Degrees grade slope 15 Degrees side slope	30 Degrees grade slope 15 Degrees side slope	30 Degrees grade slope 15 Degrees side slope
Water Disperse Distance	Fine water mist mode up to 200 ft High flow rate mode up to 265 ft	Fine water mist mode up to 200 ft High flow rate mode up to 295 ft	Fine water mist mode up to 200 ft High flow rate mode up to 295 ft

Croatian firm DOK-ING produces the MVF-5 robot (Figure 6), which comes with a 250 HP diesel engine, 2500 L water tank, and a 500 L foam tank onboard. It can speed up to 6.83

mph and can handle a slope of 30 degrees and a lateral slope of 20 degrees (https://dok-ing.hr/defence-security/mvf-5/). Its dimensions are 226" × 90" × 91"; note, the height dimension excludes the extension water monitor.

Figure 6 DOK-ING MVF–5 robot system

Austrian company LUF Ltd. developed the LUF 60 firefighting robot (Figure 7). It uses an atomized water jet, like the TAF series. Its maximum discharge range is 80 m, with a 792 gpm flow capacity. It can be remote controlled at 984 ft. It can incorporate a high-capacity ventilator to clear away smoke, heat, and toxic gases. It can climb stairs of 30 degrees and can be equipped with a bulldozer arm to remove obstacles (https://www.luf60.at/en/extinguishing-support/fire-fighting-robot-luf-60/). It has dimensions of 91" × 53" × 79".

Figure 7 LUF 60 robot system

Angatec, a French company, produces the TEC800 firefighting robot (Figure 8). It is remotely operated for fire extinguishing with a motorized water cannon. It is powered with two Li-ion batteries. The control range is 5 km (3.11 miles) using WiFi (PT90) or military grade radio (PT20). It can reach a speed of 4.5 mph, and withstand slopes up to 45 degrees, and side slopes of 35 degrees (https://www.angatec.com/en/tec800/). It has dimensions of 63" × 27" × 31", excluding the extension monitor.

Figure 8 Agnatec TEC800 robot system

Discussion

The use of firefighting robotics is emerging at a face pace, including aerial and ground robotics. The current state-of-the-art of the commercial aerial robots is nowhere close to being able to fully extinguish fires, with the payload capacity representing the major constraining variable at this point. Currently, the main commercial use of aerial robotics includes reconnaissance before, during, and after wildfires and structural fires. On the other hand, the ground robots provided in this review study have significant capacity to help with fire suppression and the cooling down of hotspots.

All twelve robots examined in this study have similar specifications and capabilities. The main limitation found is their control range, being limited to around 984 ft. Being able to control these robots from a further distance could decrease the hazard and risks for firefighters even more.

As the technology advances, and the availability increases, the prices of these robots might fall to a more affordable level for most fire departments, but at this point most base models are priced above $200,000. Most of the manufacturers did not reveal the prices except for Howe and Howe technologies and the EmiControls due to dealership agreements. Thermite RS1's base model is around $200,000 whereas the RS3 starts at $350.000. The TAF35, TAF60, and TAF60X's base models' prices are $320,000, $330,000, and $360,000, respectively, with the price going up according to the additional modules requested by the customers. The tangible benefit of this type of investment for robots is the lesser use of other firefighting resources and savings due to an earlier suppression or control of fires, while the major benefits are intangible but critical: saving firefighter lives, reducing fire-related injuries and long-term illnesses, and

saving victims lives. In addition, these robots have long useful lives, which makes the upfront cost more acceptable from a return on investment point of view.

The technology is still emerging and developing. Some improvements that could be proposed for these robots are: (1) being able to get water directly from nearby water sources such as ocean, lake, river or even a pool for fires close to these water sources (2) increased standoff ranges, and (3) the capability to control them in swarm formation.

Summary

Twelve firefighting robots were reviewed, their use cases and specifications were examined. This study could be used as a guide for first responder agencies, specifically firefighting departments across the nation to recognize the state-of-the-art of firefighting robotics. A system, where aerial robotics is used for reconnaissance and ground robotics is used for suppression efforts would be ideal to improve firefighting effectiveness and to decrease the risk of fatality, injuries, and long-term illnesses among firefighters.

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