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Impact of Digital Twins in Engineering Education: Enhancing Learning Motivation and Accessibility - A Review Study with a Proposed New Solution

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Abstract
This study presents an in-depth exploration of the implications of integrating digital twins into engineering education. Drawing on an extensive review of published research papers, conference papers, and case studies, the research is structured into several key chapters focusing on the definition of digital twins (DT), their relationship with engineering education, their influence on diversity and inclusion, and their alignment with ethical engineering principles. The study culminates in proposing a novel approach to integrating digital twins into engineering education. We propose a new lab for the mechanical vibrations course, based on the concept of digital twins, to create an identical model of the physical object, which can communicate wirelessly.

Findings from a comprehensive analysis of multiple studies suggest that the integration of digital twins has the potential to significantly enhance learning motivation and retention in engineering education. Notably, leveraging strategies such as game-centered learning, personalized learning, and virtual prototyping can effectively promote these outcomes. Of particular significance is the observation that digital twins can diversify the range of laboratory options within engineering classes without entailing additional equipment costs. Consequently, this expansion of resources mitigates barriers for students, providing them with a wider array of learning tools without imposing supplementary financial burdens or prerequisites.

1. Introduction

Use for digital twins has increased greatly in the last decade. Starting with the pandemic, a need for digital learning accelerated the research and use of this technology. The physical system was traditionally a singular physical object or machine. Now the systems have increased in complexity and with the use of modern technology can model intricate systems including social structures, economical systems, biological beings, or engineering physical systems. [2] This was the first seen used in NASA's Apollo program and was quickly adopted by the industrial and manufacturing industry to model manufacturing processes and product lifecycle. [3] Digital twins are now used in complex modeling systems, healthcare, construction management and safety, product design, education, safety training, energy usage, business models, and more. This paper reviews many different papers that each have their own definition of a digital twin, varying slightly based off their use of the digital twin.

Table 1: Digital Twin Definitions

No.	Refs.	Published Year	Definition of Digital Twin	Key Terms
1	[9]	2018	Combination of a design model with the use phase data of a product or a system	Test behavior over a lifecycle
2	[2]	2018	A mirror image of a physical process that is articulated alongside the process in question, usually matching exactly the operation of the physical process which takes place in real time	Physical replication

3	[3]	2020	A virtual duplicate of a system built from a fusion of models and data.	Dynamic system modeling
4	[6]	2020	Data flows between the physical-digital objects which are fully integrated in both directions	Control system design
5	[18]	2020	The digital replica of a physical entity utilizing the internet of things enabling two-way communications between them	Construction Management
6	[12]	2021	Represent the technology that duplicates and linkage of the physical objects and digital models	Product Design
7	[13]	2021	Corresponds to virtual twin of the real physical application which enables users to interact with detailed real-time model	Remote Laboratory
8	[	2021	Corresponds to virtual twin of the real physical application which enables users to interact with detailed real-time models.	Virtual Laboratory
9	[1]	2021	A virtual representation of a physical system (and its associated environment and processes) that is updated through the exchange of information between the physical and virtual systems	General definition
10	[15]	2022	A digital representation of a physical system, or test rig	Remote Learning
11	[14]	2022	Contain the "connection between the physical model and the corresponding virtual prototype…[and]..this connection is established by generating and transferring in both direction real-time data using sensors and actuators.	Industry 4.0
12	[16]	2022	The creation of a digital counterpart of a physical entity, whose behavior can be observed in real-time, resulting in enhanced productivity and efficiency	Digital Transformation in Engineering Education
13	[11]	2022	Comprised of a physical product, the corresponding virtual representation, and the bi-directional data transmission channel between them	Manufacturing

There are many variations in definition for digital twins. Technically speaking, digital twins are comprised of three parts: the physical system, the digital replication of the system, and continuous data flow between the two. Many newer papers today are straying from this definition. Digital twins can be confused with other similar technologies, such as digital models and digital shadows. Digital models have both the physical and digital versions of a system but lack any flow of information. Digital shadows have an exchange of information between the two systems, but the information only flows in one direction- generally from the physical system to the virtual system. [29] An example of this would be an automated sensor that takes measurements of the outside environment and sends the data to the virtual destination. [29] What distinguishes digital twins from other virtual simulations is the real time data flow in both directions between the real and virtual system. This means information can flow from the virtual system to the physical system, or from the physical system to the virtual system. Many papers use these terms interchangeably, or often mix definitions. In this paper we investigate if others address the type of virtual system they are using correctly or not.

2. Digital Twin use in general education

Education is the backbone and indicator of success in any civilization. A community with a more dedicated and widely available education system has to potential for much safer and more stable career paths, a more educated and higher achieving population. Providing an education allows for

more opportunities in better careers, and higher paying jobs. The economic success is deeply intertwined with the quality of education in a society. [47] In the modern world education is especially important. New information is being produced at a much faster rate than it used to be, shortening the lifespan of knowledge significantly, and rendering old learnings irrelevant to today. [41] New technology and information are constantly being released and updated. Students and career workers now not only need to recall what they learned in school and in trainings, but also be capable of learning new skills throughout their entire career. Learning and education has become a vital skill for not only students, but everyone in a modern and growing field. As a result, spending time to research education and how students learn is very important. To keep up these nonstop developments and changes, traditional education is not enough. [10]

Digital twins are a new technology that could potentially increase the speed of learning and make new information much more accessible. This paper reviews several different studies investigating how digital twins can improve education.

There are a variety of different methods researchers have attempted to use digital twins affectively in education including game-centered education, personalized learning, virtual and easier prototyping, and increased accessibility. Figure 1 displays the distribution of subjects withing the articles reviewed in this paper.

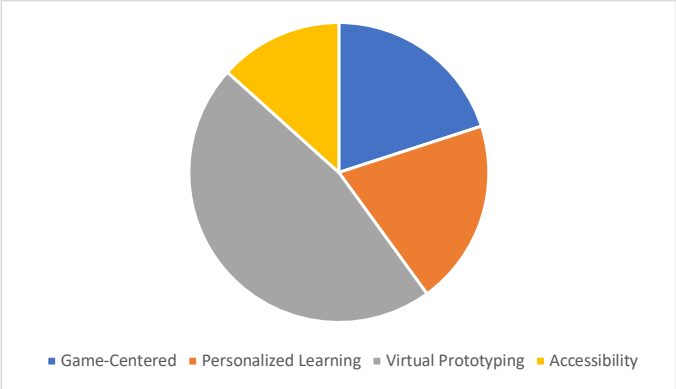

Figure 1: Main purposes of the different education goals while using the digital twin.

2.1. Game-Centered Learning

Game-centered learning provides a fun, more stimulating and interactive way for students to get familiar with a material through their own logical paths and trial and error. In some cases, it can even include the voice communication with peers. In the article [18] construction students had the opportunity to use a digital twin of a tunnel boring machine. The DT was complete with all of the different controls, steering, and a intricate environment. Multiple students could also join at once with the teacher, simulating the same environment if they were all at the machine together in person. [18] This combination of digital twins and virtual reality are a great tool that allows students to truly see what it is like to be in the given environment and become comfortable without any risk of safety or the cost of equipment. [48] Other classes such as an engineering class with a focus on heating ventilation and air conditioning class (HVAC) used a game-based DT where

students compete to get the most efficient heating and cooling system by adjusting different controls and setting. [19] Allowing students free rain to investigate different settings and properties can make the learning much more stimulating, and competition is a known motivator for many students. Particularly in a world where many younger students have grown up using technology and playing virtual games, this method of learning was received positively from students in both studies.

2.2. Personalized Learning

Traditional education was always teacher-based, where one teaching style was applied to a classroom full of students. However, all students have different learnings styles and this "one type fits all" learning approach leads to some students succeeding much more than others, with no reflection on their intelligence. A personalized DT's can analyze and remember what students know and repeatedly feel comfortable with, what they do not know, and offer helpful resources on what to learn next or similar subjects. [48] They can also provide affective feedback on how they are doing in the class. [48] This is similar to the gamification of education, because as the student "plays" the DT learning game, they are receiving instant feedback on their performance. [19] Personalized learning can also be extremely helpful for those with disabilities or are not comfortable in a traditional learning environment. For example, a DT could supply additional resources along with a lecture so that the information is displayed multiple times and in different way and can allow the student to keep up with the pace. [47]

2.3. Accessibility

Lots of information today is digitalized on the internet available to everyone. Theoretically this should make it much easier and faster to learn a large variety of topics for everyone. However, with the vast quantity of material available now on the internet, it can be very difficult and time consuming to filter through hundreds of sources and find helpful, trustworthy sources. Both papers [41] and [10] discuss how digital twins can help sort through the copeus amount of information to obtain knowledge fast with the ODIKWaV Model of Learning. This learning model is focused on making observations from your environment and drawing conclusions from them with data. Both reports explain this process takes lots of experience and practice to do efficiently and requires having a vision from the beginning. Applying the digital twins to this process, the twin can much more precisely sort through the data and information, finding the most relevant information and even identifying trends that would not be obvious to the human eye. This would allow users to stay up to date on new academic findings, keep familiar with new technologies, and stay more current with new publications in their field of interest all much faster and more efficiently than searching and doing all this manually. [10] [41]

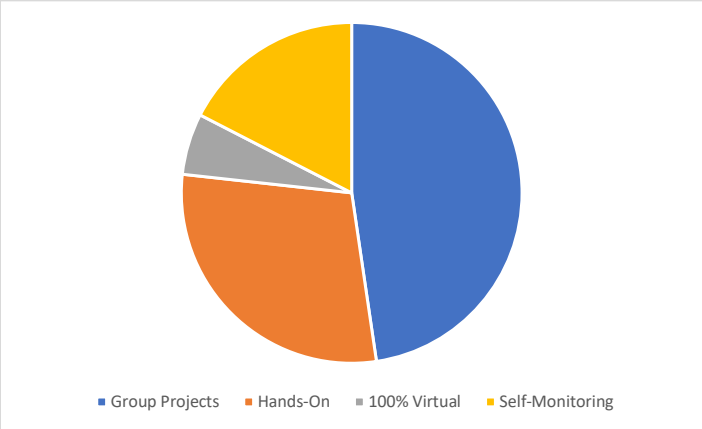

Figure 2: Different aspects of the student experiments with digital twin learning.

During the pandemic education took a pivotal turn towards online learning, and even now the online portion has stuck around as a popular option for learning. Teachers still needed to give an interactive learning experience that kept students engaged and had hands-on tools. This led way to the digital twins. Many colleges now offer online courses to provide flexibility for students. Unfortunately, many of these online classes often have much larger class sizes, as they are not constricted by a given number of seats in a physical classroom. This begins the problem of keeping students involved and interacting with the material- it is easy to hide in the back of a large class, and even easier to hide behind a screen in an even bigger class where it is harder to talk to other students. Digital twins in massive open online courses can be much improved especially in hybrid learning cases to increase interactivity through allowing access to more learning and technology. Especially in large online classes, it can be hard to connect with classmates and fully immerse themselves in the class. The use of digital twins can help make educational material more accessible and interactive for everyone. [27] Creating a way for students to interact with the material and stay involved is very important for them to get the most out of the class.

In big classrooms, there is still often one teacher. However, each student may not succeed best with that one teacher's teaching style. Digital twins can be adaptive to different student's learning styles, so they have the best opportunity to grasp the material. Digital Twins used in education can greatly enhance the learning experience by adjusting to everyone's specific learning style, benefiting equally a more diverse population of students. [41] The use of digital twins to create digital and personal education systems could greatly benefit students by having a personalized system that specifically adapts to their learning style, records what they have learned or know already, and can make suggestions on the next material. This has been coined the term symbiotic education (author) because education and learning methods should adapt and change with us. [10] Using digital twins for learning with settings for new training and quizzes to confirm students' theoretical knowledge. [23].

3. Digital Twins in Engineering Education

Hands-on laboratories are an essential part of engineering education. They provide hands on opportunities for students to apply what they have learned in the classroom and put theory into practice. However, laboratory equipment is very expensive especially with repairs or having a diverse variety of labs. Creating multiple replicas of several different laboratories or of industry equipment is not always practical and there can be additional costs to operate and maintain them. Even if the equipment is available, student access may be limited by their access to campus, time, or resources to become certified to use the laboratories. Digital twins in engineering can be a great tool as they can allow students to put what they've learned into practice. With modern developments, the physical system of digital twins can include steel structures, geotechnical engineering, coastal engineering, environmental engineering, and hydraulics. [21] There have been several examples of engineering classes who have implemented digital twins to make a more interactive and involved online laboratory section.

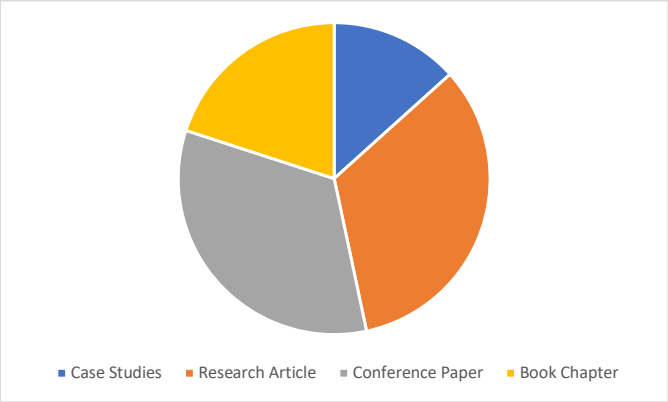

Figure 3: Types of Sources Reviewed in this Paper.

Commented [DB1]: Combine review and conference

One group of students in a mechatronics lab found and created a type of digital twin with a real-world application. These projects and results were shared through MATLAB to grant free accessibility to anyone who may wish to see it. This is a great example of digital twins being used to make the material for a class- especially a hands-on class still interactive and valuable, and allowing for creativity and creation from the students even in a virtual class. [13] This is a great example of finding a way that students still must work together and collaborate and deliver a final product using what they learned in their class. There are several other case studies of online based laboratory classes that use digital twin technology to get the students a still hands on experience. Many of these classes use additional technology to analyze and receive the data from the digital twins. A concern for future digital twin-based classes may be requiring students to have prerequisite knowledge of engineering or coding technology. Table 3 displays data from the different case studies reviewed by this paper identifying what additional technology was used in the program.

Table 2: Different Types of Hardware and Programming Used in Digital Twin Courses.

Ref.	Published Year	Number of Participants	Digital Twin Technology	Other Technology Used
[13]		42	MATLAB Simulink Design Optimization (SLDO)	Arduino
[6]		91	NX Mechatronics Concept Designer (MCD)	CAD, or Solidworks
[17]	2020	N/A	MATLAB Simulink	CPUs and PLCs
[19]		54	LabVIEW	
[21]	2018	N/A	Arduino	Processing

Digital twins allow for the expansion of different virtual laboratory experiments due to not seeking to physical, or as many instruments for the experiments. Many students still felt that they had a valuable experience and the laboratory helped them connect their lectures to real practice [15].
Digital twins can encompass parts of the engineering process such as designing, building, and testing. These steps usually take the longest and use the most material, but using digital twins would get rid of these needs. [14] The design process is very important for engineering students to have experience with before going into industry because designing a product to be within in the customer's requirements and building and testing prototypes takes practice and instruction. Using digital twins in education can not only enhance the learning of the material but has positive effects on student motivation and self-imposed responsibility to learn. This is one aspect of digital twin learning that is less explored. Digital twins, however, still cannot replace or surpass small scale personal educational settings, as the outcome of these two settings are very similar. It is better used as an additional tool to learn more advanced and specific material, or as motivation. There are also some barriers that pertain to education technology such as internet problems, cost, lack of resources, and teacher lack of knowledge to use them sufficiently. [6]

4. Digital Twins and Training for Industry

Industry is constantly changing, with new procedures being put in place, and new technology constantly being developed. Digital twins can allow a much simpler way for students to get practice and trained on the constant new uprising technologies surfacing in the world today. [16] One specific example is digital twins also have uses in flexible manufacturing systems and teaching these to students. Digital twins can be a great help here as it allows students to get very familiar with these systems and learn to use them in an easier and more accessible way. [9]
Using digital twins can also allow students to practice with industry machinery, without the school having to spend the money on the actual machinery. Digital twins can allow engineering students practical knowledge and practice with heavy machinery, planning construction sites, and even software. [18] Using digital twins to simulate real life industry situations can help students learn to prioritize tasks and work on their decision making. [20], [24]

5. Digital Twins Increasing Diversity and Inclusion

Diversity in the engineering field has increased over the last decade, and it is just as important to be aware of as the actual academic publishing within the field itself. As a STEM field, engineering requires a base level of education to even just obtain a degree in the field. Then to be a competitive potential prospect, it often takes even more education and experience. This has been a roadblock for certain people because this type of education is not as accessible in certain areas or can be

incredibly expensive. There is also a large skew in opportunities and who these opportunities are available to or in easy access to. It is important to be aware of these inequalities and work to reverse them.

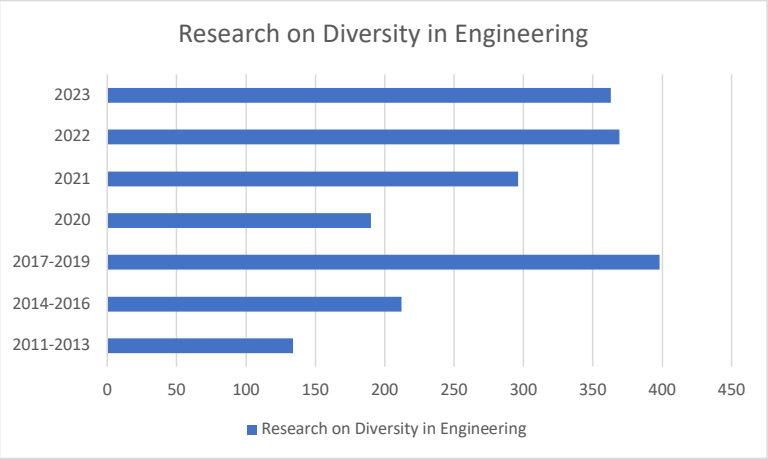

Figure 4: Amount of Research on Diversity Specifically in Engineering Throughout the last decade.

Diversity and inclusion in STEM fields was not always heavily researched or seen as important, and therefore there was not a lot of research done about it in the early 2000s. Table 7 displays the amount of research articles could be found on diversity in engineering throughout the last decade. From 2011 through 2020 there was a small but steady number of articles being published on this topic. It was not until 2021 that more research started being done. To be able to reverse this effect, those in the engineering field must understand what is causing the inequality.

5.1. How to Improve the Situation

Inequality is a problem that almost all fields and industries have had to struggle with at some point. However, the struggle is not over and there are still many places where there is a lack of diversity. To solve this problem, it must be examined on a more in-depth level. There are many different types of diversity such as racial, gender, social, and economical. Figure 5 shows the relative number of papers there are on each subset within the engineering field. Social and economic are the two areas with the most research on. The search was performed in the database ScienceDirect. One way to improve the equity within the engineering field is to improve the accessibility of the field itself. This will allow more opportunities and a larger outreach to more people. By making opportunities more accessible to allows people who are qualified but may not have the connections to easily get the high paying positions. [49] Particularly with online based sites, it is important to keep a human-centered design focus to make sure it can be easy to use and available to anyone and be effective.

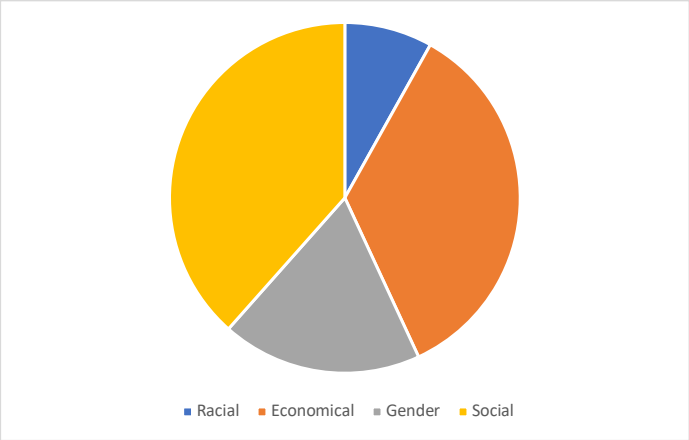

Figure 5: Different Focuses in diversity within the field of engineering.

Digital twins provide a unique opportunity in the continuous evolution to a fair, equitable field. As digital twin technology develops, it will be vital to democratize everything it keep it available to everyone without restrictions so that all have access to a better quality of life. Using digital twins can increase economical, societal, and residential growth at a faster rate. A more digital decentralized business allows a more diverse employee population that in turn can promote success in progress and evenly spread wealth in many different cities and populations. Digital twins' applications can also adapt to the user, once again creating a human-centered experience. This ca help any user be able to find and get what they need, and it can make suggestions based on what they input.

6. Ethical Engineering

Engineering education can often solely focus on the scientific and computational skills needed in industry. There is a large emphasis on math, physics, science, programming, and online modeling. This knowledge is very important to be successful in industry, but there is more that goes into engineering design than those hard skills. Equally as important as teaching students these design skills are teaching how to create human-centered designs. This means creating values for the project to keep the main goal focused on how the product can best help the lives of the targeted user and turning these values into concrete design requirements. [49] Human-centered design also means making products widely and easily accessible to everyone. As technology develops, it will be vital to democratize everything and keep it available to everyone without restrictions so that all have access to a better quality of life. A more digital decentralized business allows a more diverse employee population that in turn can promote success in progress and evenly spread wealth in many different cities and populations. [34] If new technology such as new health care tools or digital twins that can create advanced business models are given up to the highest bidder, then the already large and wealthy corporations will buy this technology and use it to continue their monopoly, preventing smaller businesses from succeeding. Making these technologies available to everyone gives smaller communities an equal chance to succeed and prosper. Engineering also

greatly relies on fact. While there is creative freedom in the design and problem-solving aspect, when it comes doewn to data the numbers do not lie. To trust the data of others and believe that their numbers are true and not "fudged" there needs to be an agreement between engineers that changing or lying about data is unethical.

However, technology can change industries and the world around us at a faster pace, and not always for the better if the human population cannot keep up. A strong ethical code regarding technology will be needed going forward to regulate and judge the new technological developments that arise. [50] Technology is being introduced into the world at an increasing pace, and as society takes in these new digital items and responds to them, it is important there are ethical guidelines set in place that can keep up. There will need to be a way to introduce the new technology to the public in reasonable, non-emotional and purely informative terms. [51] Providing the public with clear and reliable information will be vital. Not all technology will be able to be regulated, and so it is important that it can be presented in a clear way that allows the consumer public to assess the information themselves and decide on if and how to use it.

Properly educating engineers about the ethics surrounding technology can also decrease the concern. In many schools there is some form of engineering ethics training, often in the form of a class or it is mentioned in a variety of classes. All these styles can be beneficial for their own reasons and are necessary to inform engineering students of the significance of their choices are, how it will affect people, and what people it will affect. These classes are vital for deriving the purpose behind human-centered designs, what it really means and how all their designs serve a purpose or meaning to someone intentional or not. Students must become aware of their professional, ethical, and social responsibilities when making an engineering decision. [54]

For those who create this technology there are many concerns that online they can abuse their power and access they have to people. Some of these concerns include privacy, electronic commerce, control of essential facilities, and biogenetic engineering. [51] With more and more online users, people are becoming more open with their information. Numerous sites ask for personal information to create an account and become a user, to create a secure login, to send the users consistent information to stimulate more usage, and even direct questions to learn more about user demographic. While some of this information can provide beneficial knowledge to the creators, there is a fine line between helpful knowledge and overexploitation. It is vital to get many different opinions in the world field to best predict these effects and find ways to avoid them. It is also important to acknowledge that certain technologies or parts may affect different demographics differently. It is important to have a diverse group of people working together to best moderate these effects because they all have different perspective on how they may have been affected in the past, or how they have seen particular people get affected and can offer valuable input. [52] In order to have truly human-centered designs and products, they must be made available to everyone in a low-risk setting. [53]

7. Our Solution: Enhancing Learning Motivation and Accessibility using Digital Twins

This study has provided a comprehensive overview of the current state of digital twins, elucidating their various applications and the evolving landscape of this emerging technology. With a thorough understanding of digital twins and their versatile capabilities, our focus now shifts towards proposing an innovative educational application within the context of the Cal Poly education center.

Digital twins, as a nascent technology, exhibit tremendous adaptability across diverse industries. In the realm of education, we aim to explore the feasibility and productivity of integrating digital

twins into the curriculum at Cal Poly. Our specific proposal involves the development of a cost-effective vibration analysis and fault detection hands-on laboratory for undergraduate engineering students specializing in mechanical vibrations within the Mechanical Engineering department.
In response to the challenges faced by educational institutions, particularly the cost and complexity associated with implementing advanced technologies, our primary research goal is to democratize access to vibration analysis technologies. We envision achieving this by creating an affordable and efficient monitoring system tailored for educational purposes.
Outlined in Figure 6, our proposed system features a physical vibration setup, including a cantilever beam, and a Bluetooth sensor transmitting raw data to a computer. Simultaneously, a Finite Element Method (FEM) model of the cantilever beam is generated. This hardware setup is complemented by a machine learning model trained on synthetic data, generated using MATLAB. This innovative approach eliminates the need for expensive and time-consuming experimental setups, expediting the model training phase and reducing overall costs.
Through the implementation of this laboratory, students gain hands-on experience in vibration measurement setups, wireless communication, computer simulation, machine learning applications, and fault detection techniques. By seamlessly integrating theoretical knowledge with practical skills, our solution aims to enhance the learning motivation and accessibility of advanced engineering concepts, ultimately contributing to a more comprehensive and inclusive educational experience at Cal Poly.

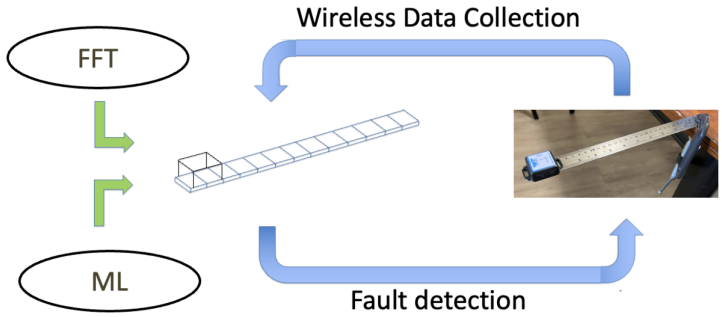

Figure 6: system and operation

In the future if this research is to be continued, one of the next steps will be to create a questionnaire to give out to others and receive feedback on this topic through the international review board (IRB). The IRB reviews research proposals and questionaries with a diverse panel of reviewers to ensure the proposed research is following human rights guidelines and using ethical practices. [54] The goal of this process would be to gain further understanding on what the student and staff body of Cal Poly knows about digital twins and their effects. It is important to learn more about the desired group's prior knowledge to this new technology and gauge their interest in it. Below are a few sample questions that could be asked:

1. Have you ever heard the term "digital twin" before?
2. Where have you seen the term "digital twin" used before?
3. What is your best definition of a digital twin?

4. Digital twins are a replica of a physical entity utilizing the internet of things enabling two-way communications between them. [18] Knowing this how interested are you in learning more about digital twins?
5. Do you think learning how to use and create digital twins would be useful to you in industry?

Understanding more about how much the students and staff of Cal poly know about digital twins will help us determine our next steps in this research. If digital twins are implemented into the curriculum, we will know how much prior knowledge the students have and how much additional training will have to be done. This applies to the teachers as well- if they are unfamiliar with the topic they will not be able to teach it. Considering this another future step will be to meet with the engineering teachers of Cal Poly and analyze their classes to determine if digital twins could be helpful in their courses.

6. Conclusion

Digital Twins used in education can greatly enhance the learning experience by adjusting to everyone's specific learning style, benefiting equally a more diverse population of students. [41] Data driven methods could help create unbiased and equity-based solutions for cities and plans such as evacuation or natural disaster plans, or design plans. [43] To control the advancement of digital twins there should be some sort of organization perhaps through the government that will monitor the growth and uses of digital twins to ensure equal advancement for all persons and that it does not fall into high up corporate hands to use. [42]

Figure 7 is a representation of how many research articles were published within each time span and separated by each subject regarding digital twins. This search was done on the database ScienceDirect, to provide a more filtered and reliable result list than Google Scholar. This chart also only considers research articles, because using research articles, book chapters, and review articles may result in some repetitiveness in the content that is read and want to focus on different studies and raw data that has been taken over the last decade. Key words were used to get a more specific results list including the terms "digital twin", "manufacturing", "education and learning", "diversity", "equity", "inclusion", and "smart cities." The results show there was a strong original interest in using DTs within the engineering and manufacturing fields, and that interest has continued to grow. Within the last decade there has been an increase in interest in researching the use of digital twins within education, and hopefully that will continue to grow as education and learning is the backbone of any other rapidly evolving field. There was also not much interest in the effect of digital twins on diversity until 2020, and in 2023 there is still a very low number. There needs to be a continuation of research in these fields, as digital twins represent a very high potential technology that can be applied in an extremely diverse number of environments and for different purposes. Their adaptability is why it will be able to keep up with the constantly changing technology and world and be able to help its users also stay up to date.

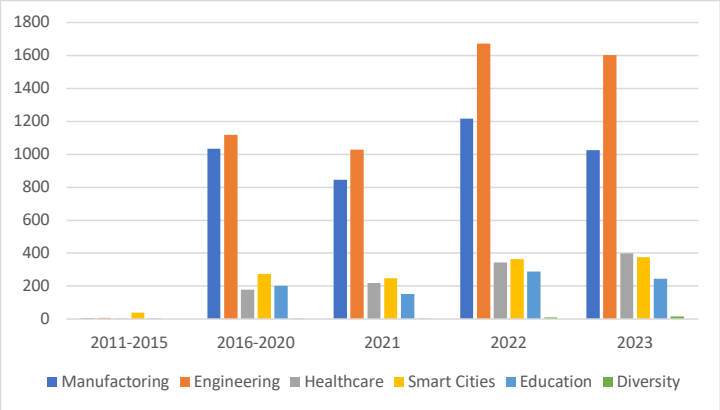

Figure 7: Published articles on different digital twin subject from 2011-2023

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