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CASE STUDY OF CONNECTIVITY OF DIGITAL TWINS AND EXPERIMENTAL SYSTEMS

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Abstract. *One of the main usages for a digital twin is the centralization and utilization of numerical, physics, and experimental based data. While there has been a large amount of research in the definition and utilization of computer simulations, there exists a gap in research in the interaction between experimental setups and digital twins. This work focuses on an example of how an experimental setup can interact with a digital twin via an operational platform. The experimental setup for this work is a scaled 3 storey building excited with a 6-DOF ground shaker under various controlled environmental conditions. For the digital twin, a server-based operational platform is used to allow for interactions with the digital twin from any remote operation site. The work in this paper gives an example of how the digital twin and experimental setup interacts and explores the added benefits of using a digital twin in experimental research.*

Keywords: Digital Twins, Operational Platform, 6-DOF Excitations, Environmental Testing

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1 Introduction

In the current state-of-the-art, digital twins are typically comprised of purely experimental (pre-digital twins), or physics (numerical twins) based models [1]. It is currently rare for digital twins to incorporate both types of models in a meaningful capacity. This has lead to a greater desire in research to incorporate both experimental results and physics based simulations into a single digital twin to be useful for an analyst. The research presented in this paper is a case study for the centralization of experimental and numerical models into a digital twin.

The concept of "twinning", the art of using a one-to-one surrogate for generating diagnostic/predictive information, dates back to the NASA Apollo missions used for training astronauts and diagnostic testing [2]. However, recently there has been a greater focus on the development of digital twins that allows easy access to both accurate physics based simulations and experimental data performed. This will lead to the utilization for decision making, such as determining a maintenance schedule [3].

Some initial work has been done in the combination of experimental data and numerical simulations, such as the work done in [3, 4, 5]. The majority of this work is focused on what is termed "grey-box modelling" that uses a combination of physics based models and experimental data to create a surrogate model. While this work is important for the use in digital twins, the work presented in this paper focuses on how the information is passed between the experimental data, physics based models, and the analyst via an operational platform.

The Digital Twin Operational Platform (DTOP) is the interface that an analyst uses to create models, investigates numerical and experimental results, and create predictions based on the available information. There are multiple methods researchers and companies have used to develop operational platforms. Currently, a majority of available digital twins are operated via an executable that can interact with a database or live sensor data. This, although designed as such, limits both the number of people and whom can interact with the digital twin. Using an executable is useful if only a small number of analysts are expected to use it, for example in a power generating facility, however researchers tend to have a larger number of analysts at various locations. In order to aide researchers in using a digital twin, this work focuses on an web based platform that is accessible to any approved analyst with internet access.

With a web based platform, there is greater access to the DTOP, even at remote locations such as test sites. However, there are connectivity issues between local hardware and the DTOP. This work will demonstrate a case study for one method to combine the local hardware used in experimental testing with the web based DTOP. Section 2 will describe the hardware setup and testing conditions tested on the demonstration system discussed in Section 2.1. To discuss the web based DTOP, Section 3 shows the generated digital twin for the demonstration system and discusses some of the selected options used for the demonstration system and alternatives for each option. Section 4 discusses the interactions between the DTOP and experimental setup and demonstrates some of the added benefits to using a digital twin with experimental systems in Section 4.1. Some concluding remarks are presented in Section 5.

2 Experimental Setup

The main purpose of these experiments are to characterize the combined effects of environmental temperature and added masses on a civil structure. More information about this system is given in Section 2.1. To test this combined effects, the advanced facilities at the Laboratory for Verification and Validation (LVV) at the University of Sheffield. The LVV is equipped with multiple environmental chambers with one specifically designed for shaker based vibration testing. This specific chamber is able to operate from -50 to $50^{o}C$ with a shaker able to exert a maximum acceleration of 3g.

To study the combined effects on this structure, a suite of tests are performed at multiple temperatures with various added masses. For each temperature, the four values of added mass are 0.0,5.72,11.44, and 18.2 Kg. Relative to the structure mass, this is 0%,4.0%,8.0%, and 12.7% respectively. These proportions are thought of as a high percentage, but still realistic for civil structures. The temperature range of interest is based on yearly range in a seismically active region. Specifically, northern Japan is used that has a typical range between -10 and $30^{o}C$, so the testing is performed on a slightly expanded range of -15 to $35^{o}C$.

For each combinations of temperature and added mass, a swept sine excitation is applied via the 6 degree of freedom shaker. This excitation was applied in a single direction with frequencies ranging from 3 to 30 Hz with a linear rate of 0.1 Hz/s and an amplitude of 0.8 m/s^2. This range is based on the first three bending modes obtained by preliminary tap tests where the third natural frequency is near 25 Hz. Although this paper focuses on the connectivity between the experiment and DTOP, these tests are also used for other work that focuses more on the grey-box modelling.

2.1 Demonstration System

The experimental system tested in this work is a scaled 3 storey building. This is constructed using extruded T-slot aluminium that is mounted to the shaker table. The general dimensions of this building are 2.42 m tall with a cross-section of 930x820 mm. A photo of the test system mounted to the shaker table within the environmental chamber is seen in Figure 1.

Figure 1: 3 storey building

One aspect of the experimental system is the sensor layout. For these tests, there are two single-axis accelerometers for each pillar on each floor with a total of 24 accelerometers. In addition to these 24, there is also a baseline accelerometer on the shaker table to measure the input and additional sensors on a single pillar at the half floors to identify if there are any local modes in the support pillars experienced for this system in the range of interest. As a validation for this system, a calibrated beam model is generated. This model has an adjusted Young's modulus because the exact heat treatment of the aluminium is unknown, to match the first three bending frequencies that was obtained through some preliminary impact hammer testing. The accuracy of the calibrated model for the first three natural frequencies are within 1.5%.

3 Digital Twin Operational Platform

The most import aspect of communication between a user of the digital twin, the stored information, and the experimental system is the Digital Twin Operational Platform (DTOP). Using a DTOP is a useful method to inspecting information for the digital twin, with an emphasis on the ease-of-use. The main goals of a DTOP is to perform six main operations.

1. Access the collection of simulation, experimental, and historical results to aid in decision making
2. Provide access to approved users
3. Maintain data security and redundancy
4. Schedule/perform novel simulations for the digital twin
5. Access real-time data from live sensors
6. Interact directly with the physical twin

These six goals of a DTOP represent all the needs expressed for the operational platform aspect of the digital twin. While there is currently a large amount of work being done in order to ensure that the digital and physical twins perfectly correlate, this work focuses on the access to information and the user experience (the so-called human-computer interaction). For this particular work, a large focus is placed on the first two operations listed above.

While discussing the access to digital twins via a DTOP, it is import to denote some of the different frameworks available. One of the most important frameworks is the accessibility of the DTOP to users. To discuss how a user can access a digital twin, Figure 2 shows the 3 main methods to access a digital twin via a DTOP. There are both advantages and disadvantages for each method.

The first method to access a DTOP is based on being stand-alone. This method is where a local version of the digital twin is accessed, typically through an executable. All the information from experiments, simulations, and sensors are all stored on a single machine. This provides maximum information security, however, it greatly limits the amount of work that can be performed. A common use for a stand-alone DTOP is in an energy producing plant. This example is more focused on the daily operation and predicting the needed controls under various circumstances. These types of use-cases require extremely high security and doesn't have a large number of simultaneous users.

The second method to access a DTOP is through a Local Area Network (LAN). This method is an expansion of the stand-alone by allowing access to the DTOP for multiple users on the same network. In addition to having multiple users, the LAN method also allows the utilization of distributed computing. If the site has a local high performance computer, this method can

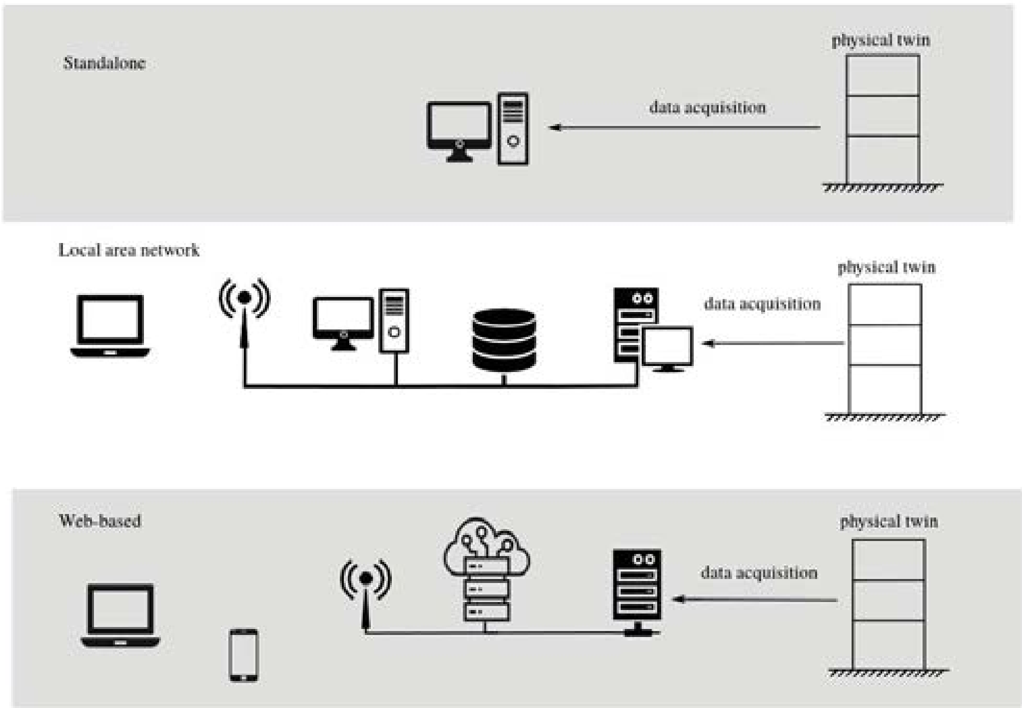


Figure 2: Different methods to access digital twins via a DTOP

utilise it in making predictions and other calculations. This method is an expected use case for the design and operation of complex systems. One example would be an aircraft, where there are multiple aspects being evaluated simultaneously, such as structural and electrical design/repair. While there is the ability for multiple users, this method also has high data security by only allowing people physically on the network to access this information.

The final method is the web-based DTOP. This greatly expands the number of possible users to anyone allowed access and internet access. Having this large accessibility encourages collaborative work and greatly expands the possibilities available. One such possibility is the ability to easily have remote sensors and monitoring a system after deployment. This method is particularly of interest for research systems, civil structures such as bridges, and large scale designs to incorporate multiple facilities at various locations.

4 Connectivity Example of Digital Twin and Experimental System

In order to demonstrate the connectivity aspects of a DTOP, an example DTOP is created using the demonstration system. This DTOP utilizes the web-based method since the testing and analysis are performed at separate locations due to social distancing requirements. To structure the web-based framework, two actions are performed. The first action is the utilization of the python code FLASK to create a webpage template to act as the user interface. FLASK uses python as a programming framework and HTML/CSS for visualization and navigation. This framework using FLASK can be used for any of the previously mentioned access methods (stand-alone, LAN, or web-based).

It is simple to utilise FLASK for a stand-alone or LAN version, but to use it as a web-based DTOP, a hosting service is required. This hosting can be done through a supporting organization, such as an University, or via a private host. For the second action of this example DTOP, a service called Heroku is used to host the DTOP. Heroku was chosen for a few reasons including a free tier of hosting for demonstration purposes, virtual computations, and database hosting, but there are many other possible hosting services available that may fit other applications better.

There are two main simulations currently implemented in this DTOP, the first being a parametric beam finite element model. This simulation produces an ABAQUS run script then calls ABAQUS to run the simulation. The other simulation, and the main focus of this paper, is for post-processing the raw experimental data. A PostgreSQL database is utilized to store the raw experimental data and is implemented using the Heroku service.

To demonstrate this example DTOP, the main navigation page is displayed in Figure 3. This contains two main sections; The first section on the left side is a selection of the implemented simulations. This section allows the user to select which simulation they wish to perform. The other section on the right is an interactive visualization for the system of interest. This gives an "as-designed" geometric understanding of the system. One interesting aspect is that the extruded aluminium portions of the system are given directly from the manufacturer.

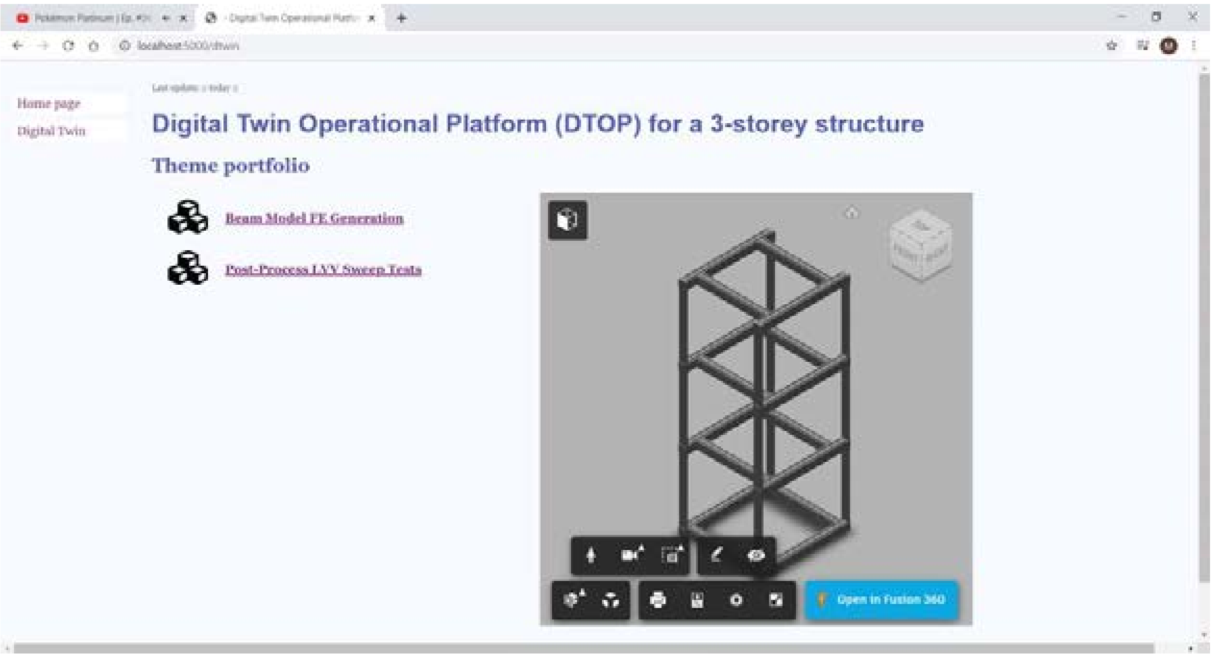


Figure 3: Main Navigation Page of DTOP

In the current implementation, there is no live streaming of the sensor information. This is primarily due to some of the proprietary software associated with controlling the environmental chamber and shaker. A prototype of streaming the sensor information is currently in development but is not the focus of this work. Instead, the data from the sensors is recorded then uploaded to the digital twin database. This upload is possible to implement within the DTOP, but currently is not to ensure a consistent data-structure. Currently, a separate python script is run that gathers the correct meta-data and stores that information and sensor data to the database.

For the post-processing aspect of the DTOP, there are two steps to perform this analysis. The first step is the selection of what experimental data to process. To aid the user with this selection, the DTOP queries the database to produce a list of available experimental tests that the user can select via a drop-down menu option. Once a test is selected, the next step is performing the post-processing and visualization. This visualization is displayed to the user with an example shown in Figure 4. The results shown are for a test at $25^{o}C$ with no added mass.

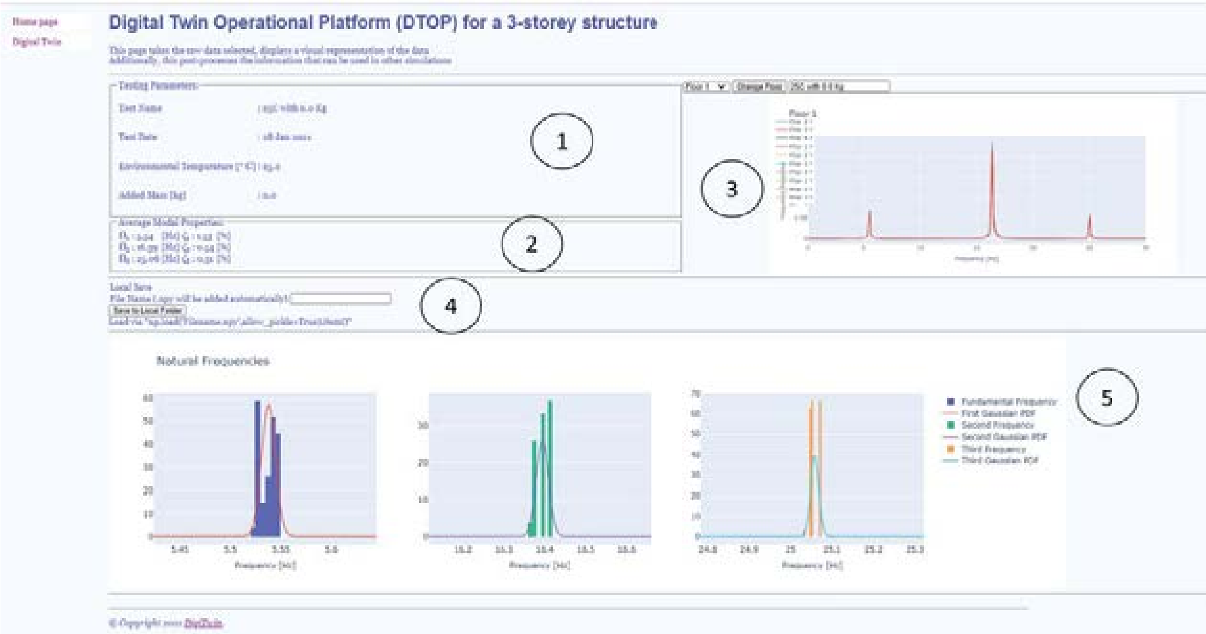
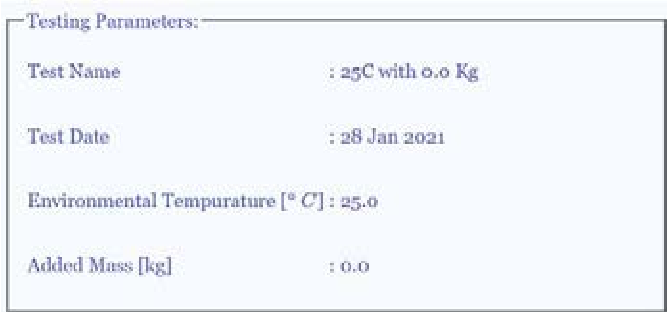


Figure 4: Post-processing page of DTOP

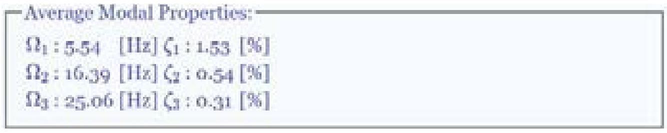
There are five main parts to the screen in Figure 4. The first part is an expression of the meta-data. This part gives users the testing parameters such as temperature and added mass, along with the testing date and name. Part 2 gives the scalar post-processing values. These values are the natural frequency and damping ratio for each of the three bending modes. The natural frequency is calculated via a peak picking routine and the damping is determined by a half-power method. Part 2 shows the values for these quantities by averaging all the excitation direction sensor results for the 3 repeated tests per configuration. Both of these are shown in greater details in Figure 5.

Part 4 allows for downloading the database entry onto the local drive, and can be seen in more detail in Figure 5c This saves 6 pieces of information in a dictionary that is saved via a .npy file. These are lists containing the sensor names, time history, and PSDs. Additionally it also saves the meta-data and vectors containing the time and frequency for the time history and PSD information. Part 3 of Figure 4, with a closer view in Figure 6, shows the auto Power Spectrum Density (PSD) for a number of the sensors to denote some of the differences between sensors and tests. Since there are a large amount of sensors, this part is categorized based on the sensor location. In the current implementation, these sensors are categorized based on which floor they measure. The user can select which floor to visualize via the drop-down menu.

The final part is a measure of the variability for the calculated scalar post-processing values, specifically the natural frequencies. This shows a histogram of the calculated frequencies used in part 2 and a fitted Gaussian distribution to the same data. The first natural frequency is shown in Figure 7 with the histogram in blue and the fitted Gaussian distribution in red. This plot takes a total of 54 sensor readings to create this histogram.



(a) Part 1 - Testing parameters



(b) Part 2 - Average scalar post-processing values

(c) Part 4 - Local save option

Figure 5: Text-based reported post-processing

4.1 Added Benefits

Using a DTOP with an experimental system provides several benefits to both the testing engineer and the analyst. One of the greatest benefits is the data storage and access. In a traditional approach, the data is stored locally in a variety of formats depending on the software used and engineering preference. After the data is collected, it is then transferred to the analyst either via email or physical transfer such as with an USB removable drive. This requires the analyst to understand the format used by the test engineer and be able to transform it into a usable format for the analysis.

For a large amount of cases, the data is too large to send via email and the analyst is typically not at the testing location. In some cases, the analyst might be in a different country where the delivering of a physical transfer would introduce large amount of wasted time. Using a DTOP centralizes the data and allows access to an analyst at any location in an easy to understand format. This only requires the testing engineer to submit the test results to the database, and the analyst can investigate the results via the DTOP. After investigating the results, the analyst can ensure the accuracy of the tests, suggest additional testing configurations, and perform advanced calculations/predictions in a timely manner.

In addition to the efficiency increase, using a DTOP also greatly increases the collaborative nature of projects and increases visibility of the project for marketing purposes. Because the data is stored virtually, access can be granted to any collaborators regardless of physical location. In the same sense, the DTOP can be used for demonstrating the project potential, show preliminary results without the need to transfer information, and to give a live demonstration of the digital twin.

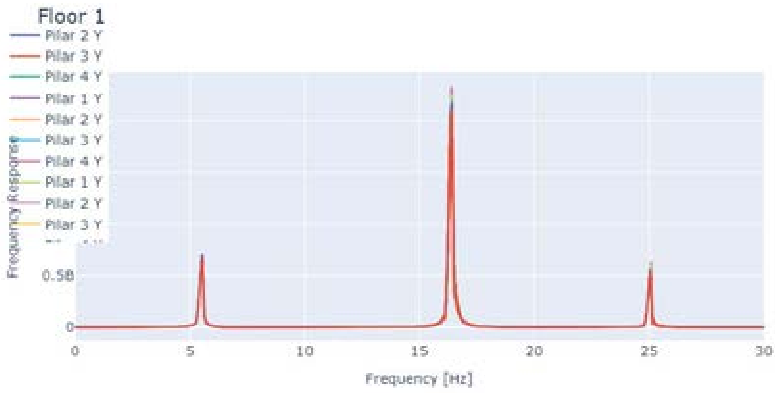


Figure 6: Part 3 - Power spectrum densities

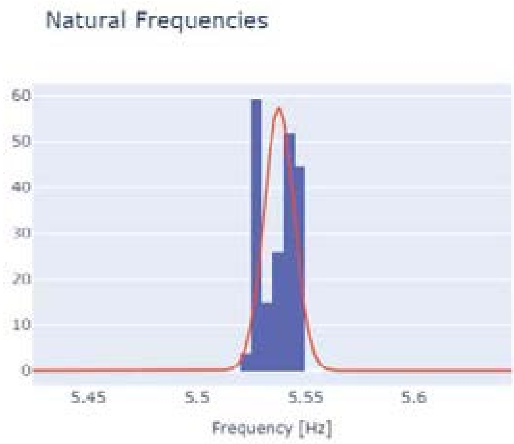


Figure 7: Part 5 - Histogram of fundamental frequency

5 Conclusions/Remarks

This work demonstrates a case study of how an operational platform can benefit experimental operations through increased connectivity to analysts and simulations. The connectivity is based on the use of a web-based digital twin operational platform. This allows the experimentalist to upload experimental results and for an analyst to access this information via an easy to use interface with high time efficiency due to the reduced data transfer time.

This paper presents an example operational platform that gathers the experimental data from the database and performs post-processing on it from any device that has an internet connection. These calculations are performed virtually so there are no hardware requirements to view the data. This is particularly useful for demonstration purposes to present results without the need to ensure correct data transfer.

The operational platform also highly encourages collaborative works where researchers from different universities or companies are able to access and supplement all the collected simulation and experimental data. With all of these benefits, an operational platform, particularly for digital twin purposes, provides a useful user-interface for the collected data, perform additional simulations, directly interact with the physical system, and promote collaboration and efficiency with both local and global partners.

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