Digital Twin Assessments in Virtual Reality: An Explorational Study with Aeroengines

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Abstract—We present an immersive environment where Virtual Reality (VR) is used to visualize the performance of a fleet of aircraft engines. Our virtual environment uses 3D geometric computer-aided design (CAD) models of the engines paired with performance maps that characterize their nominal working condition. These maps plot pressure ratio and efficiency as a function of shaft speed and inlet flow capacity for the numerous engine sub-systems. Superimposed on these maps is the true performance of each engine, obtained through real-time sensors. In this bespoke virtual space, an engineer can rapidly analyze the health of different engine sub-systems across the fleet within seconds. One of the key elements of such a system is the selection of an appropriate interaction technique. In this paper we explore the potential of interaction methods supported by a combination of gaze-tracking and hand-tracking achieved via an additional sensor attached to the front of the VR headset, with no need for the user to hold a controller. We report on an observational study with a small number of domain-experts to identify usability problems, spot potential improvements, and gain insights into our design interaction capabilities. The study allows us to trim the design space and to guide further design efforts in this area. We also analyze qualitative feedback provided by the end-users and discuss the lessons learned during the design, implementation, verification and validation of the system.

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1. Introduction

Digital twins are multi-scale, multi-physics, probabilistic computational representations of real engineering assets [1]. They are designed to characterize and model key input-output dependencies, based on data acquired from sensors on the monitored assets and physics-based knowledge that is encoded in varying fidelities of computational tools. These assets can range from bridges and buildings to jet-engines and airplanes. More physically representative digital twins empower engineers to gain better insight into their system's operation, offering the ability to make more well-informed decisions. This newly emerging field of *data-centric engineering* (see [2], [3], [4], [5] and references therein) is a unique pairing of advanced computational statistics with engineering principles and is ushering in a new era of digitization across all branches of engineering. The focus in this paper will be on such assets within the aerospace sector specifically tailored for aeroengines.

The increase in digitization within the aeroengine sector is concurrently taking place with an increase in new human-computer interaction techniques. This should not come as a surprise, as improvements in the former can be catalyzed by the latter. One propitious human-computer interaction pathway has been that of virtual reality (VR), where bespoke 3D environments can be constructed, and users can leverage a range of different interaction paradigms, including visual, audio and even haptic feedback. It is thus natural to think of VR as a well-suited environment for (1) interactive visualization; and (2) analytical reasoning for complex multidimensional data—in this paper for aeroengine design, build and operation.

Bringing together these two avenues for cognition, we can think of having a *Visual Analytics* system as first defined in [6]. These ingredients, coupled with the newest advances in the field of so-called immersive technologies, which includes not only VR, but also Mixed Reality (MR) and Augmented Reality (AR), have given rise to the new research field of *Immersive Visual Analytics* [7]. This research field uses the immersive environment as the main medium for interactive data visualization and consequently investigates how to effectively design (and use) such systems. However, there are still a number of obstacles that need to be overcome for mass adaptation of such tools. For starters, there is the need of demanding computing resources required to support costly VR
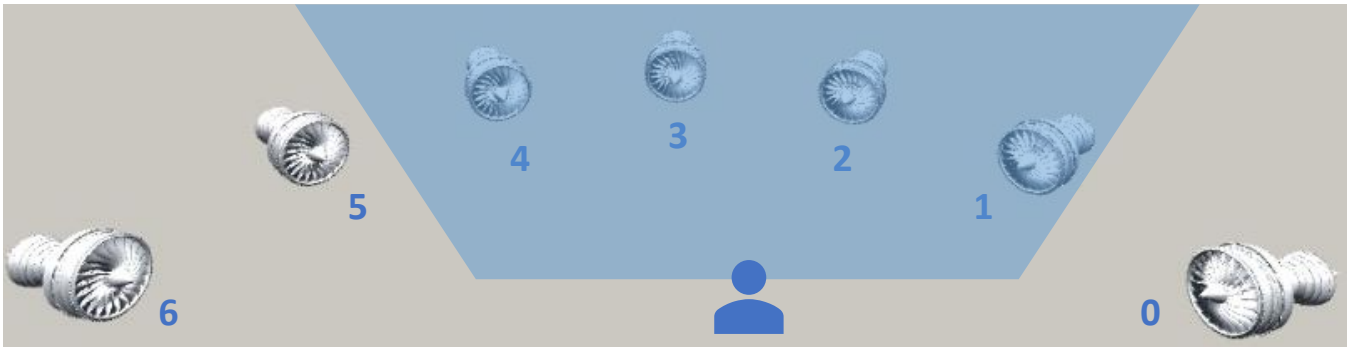
Figure 1. **The array of aeroengines CAD models arranged in a counterclockwise ordered around an arc in equal steps centered around a user's avatar. Assuming the engines are not moved or the user's avatar does not change its position, at most four engines will be visible in the user's field of view.**

infrastructure [8]. Then there are occlusion effects [9], which plague nearly all 3D interactive paradigms. Finally, there is the challenge of demonstrating that VR promotes more efficient visualizations that lead to more effective reasoning, when compared with today's existing modes of user-data engagement. That said, some strides have been made in abating these barriers to entry and acceptance. For instance, with regards to infrastructure, recently, a new wave of wireless, standalone VR headsets have been introduced (e.g. Oculus Go or Oculus Quest [8]) which diminish the barrier to entry in terms of the costs for the novice users. Additionally, new interaction methods used to interact with VR-based environments are currently being investigated, including coupling gaze and hand tracking [10].

These developments set the stage for our paper. We study the health of a fleet of aeroengines (see Fig. 1) in a bespoke VR environment that seamlessly blends computer-aided design (CAD) models of the engines with a series of interactive analytical graphs that reveal the performance data of each engine. Our environment, tailored for the aeroengine engineer, is designed to permit (i) rapid comparisons between engines; (ii) facilitate fault detection; and (iii) enable a greater understanding of the location of various sub-systems, components and the interactions between.

2. RELATED WORK

The application of 3D interfaces, such as the one envisioned by pioneer Ivan Sutherland [11], to aid research in aeronautics and astronautics, has a decades-long history. For instance, one of the first attempts to use a VR environment for the purpose of aerospace design can be found in 1994 [12], [13].

More recently García-Hernandez et al. [14] discuss the use of VR for data mining and information visualization, listing aerospace as a potential sector ripe for VR application. Specific applications of VR in aerospace include that of *aerodynamic design* (see also [15]) and even *spacecraft design optimization* (see also [16]). Three areas have been previously recognized as especially promising for successful application of VR: (1) Parallel Coordinates Plots in 3D (see, for example [17] [18]); (2) complex graph visualizations; and (3) obtaining 3D data by integrating multiple 2D plots [14]. In this paper, we study VR parallels for (2) and (3).

A myriad of other application areas at the crossroads of immersive analytics, VR and aerospace exist. This list includes, among others, collaborative environments (see [19], [20]);

usage of the haptic feedback (see [21], [22]); planetary exploration (see [23]); simulation in aerospace and aeronautics (see [24]) or visualization of sensor data and telemetry (see [23], [25], [26]).

Russel et al. [25], present an interactive VR-based visualization for complex systems diagnosis and health management in rocket engine tests that aid non-expert users in rapidly gaining an overview of the system's operating status and health. In a similar vein, Lecakes et al. [26] discuss a VR environment for visualization of measurements of sensory data to support the operator in prompt assessment of system health. Finally, Wright et al. [23] offer an interesting discussion of telemetry data visualization using CAD models linked with the associated sensor data. They introduce the notion that a change in a linked data stream could result in an appropriate change in the model visualization as well. In comparison to these studies, although we do combine CAD models together with graph visualization, we focus on using a new, alternative way of manipulation via gestural input facilitated by a hand-tracking sensor [27].

3. AEORENGINE VISUALIZATION SYSTEM

In what follows we detail particulars of our aeroengine visualization system. The whole visualization was written using the Unity game engine [28].

Apparatus

The experimental and development setup consisted of NVIDIA GeForce GTX 1080 GPU and an Intel i7-7700K 4.20 GHz CPU working under the Windows 10 Pro 64bit operating system with 32 GB of RAM. The VR environment used an Oculus Rift [8] head-mounted display (HMD). Hand-tracking was permitted with the Leap Motion sensor [27] attached in front of the HMD, and gesture recognition was developed using the Leap Motion SDK [27].

Aeroengines Models

The system consists of an array of an interactive aeroengine CAD models [29] arranged in equal steps along a semi-circular arc in front of the user's initial position and gaze direction, as shown in Fig. 1. In our case, for testing, we use seven aeroengine models. However, the number of aeroengine models can be easily adjusted depending on a particular user's needs and wants. Each of the models consist of eleven subsystems, including low (LPC), intermediate (IPC) and high pressure compressors (HPC). These
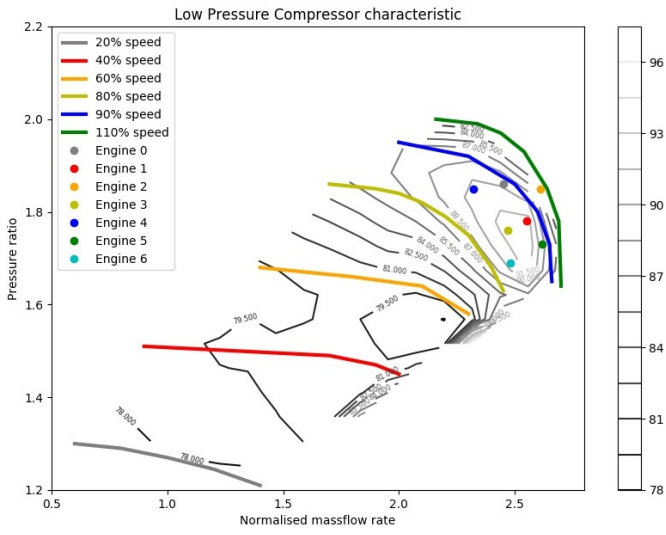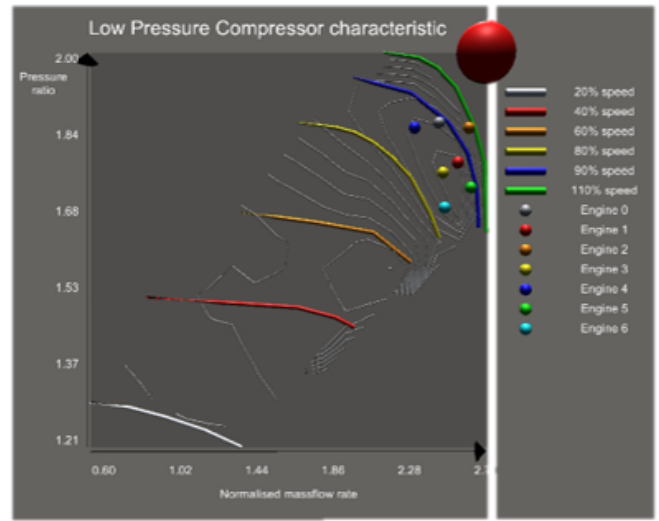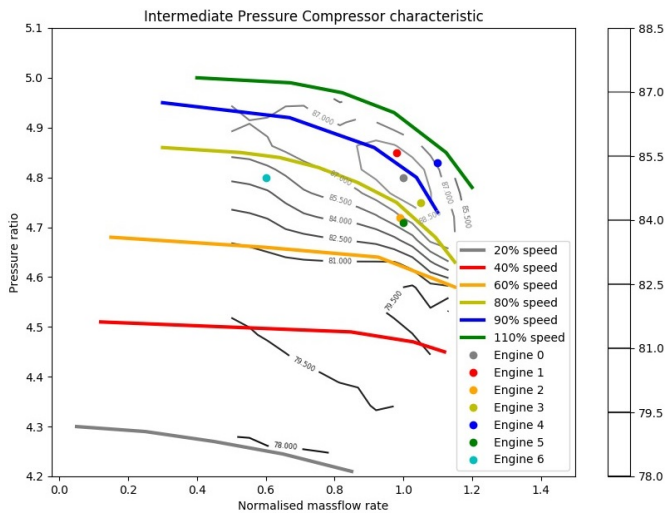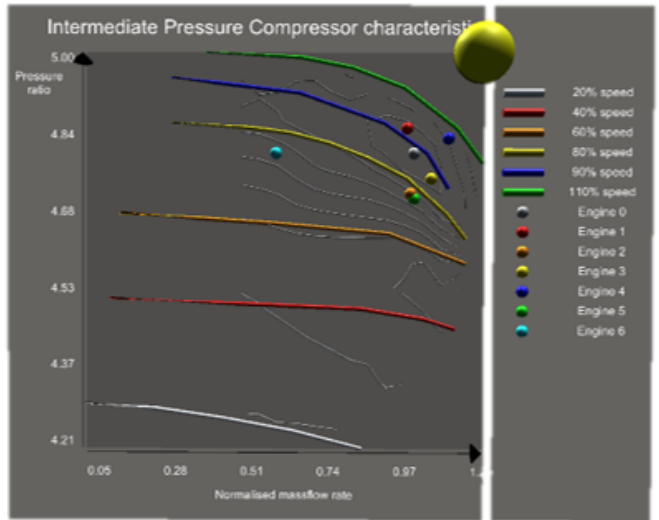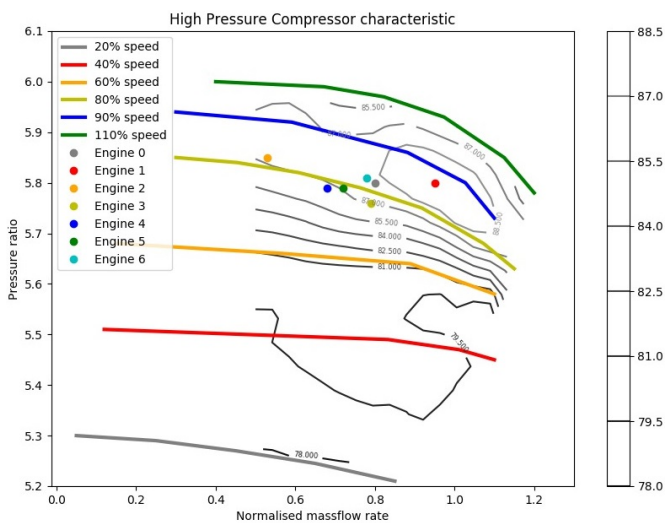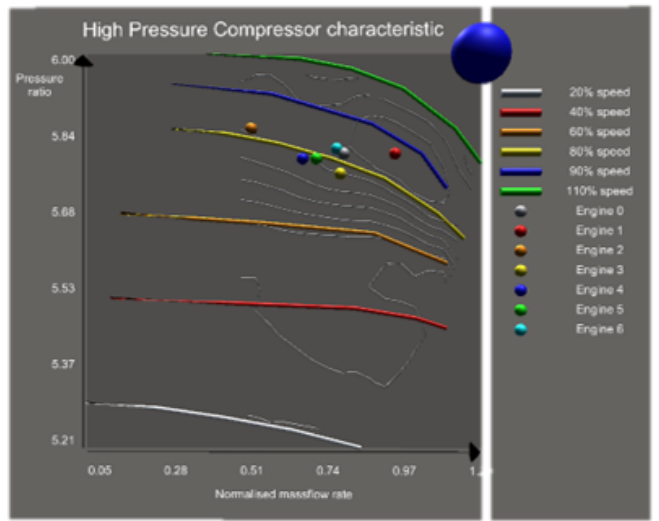
Figure 2. **The compressor characteristics plots viewed on a standard desktop monitor (a, c, e) and how they are presented to the user in VR (b, d, f).**
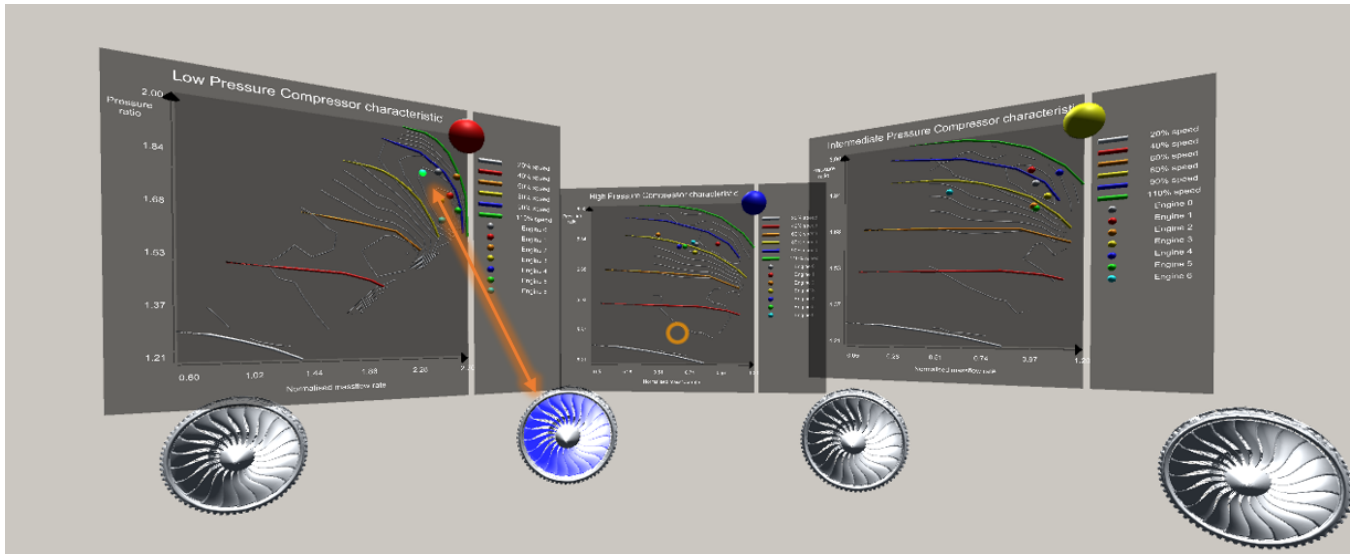
Figure 3. **The three graphs represent the current conditions of the three types of compressor: the low (LPC), intermediate (IPC) and high pressure (HPC) compressors for each engine. These three plots, from left to right, are shown in detail in Fig. 2(b), Fig. 2(d) and Fig. 2(f) respectively. Moreover, the selection of one of the LPC's operating points automatically selects the accompanying LPC component on the associated engine model as indicated by the orange arrow. The same is true for all of the other compressor characteristics graphs as well.**

three compressors—standard subsystems for a three-shaft aeroengine—form our main subsystems of interest.

The full list of the available engine sub-components that do not contain any sub-parts themselves consist of these eleven elements:

1. Casing
2. Low pressure compressor (LPC)
3. High pressure compressor (HPC)
4. Intermediate pressure compressor (IPC)
5. Low pressure turbine, shaft and nozzle
6. Fan
7. Nose cone
8. High pressure shaft
9. Intermediate pressure shaft
10. Intermediate pressure turbine
11. Combustor and high pressure turbine

Compressors Characteristics Plots

Each of these three compressors are accompanied with interactive performance maps that characterize their nominal working condition. These maps plot the pressure ratio and efficiency as a function of shaft speed and inlet non-dimensional massflow rate for the numerous engine subsystems, as can be seen in Fig. 2. The first column of the plots shows them as they would be seen by someone using a standard 2D screen. Here the pressure ratio is shown via a series of *constant speed* colored lines while the efficiency is depicted via grey iso-contours. The operating point of each engine on these characteristics is shown via a series of circular markers. The second column shows the same plots as they are depicted in the VR environment. Note that the iso-contour lines and the lines are in 3D (i.e. not flat). The operating points of each engine, marked as a set of small, color-coded spheres embedded in the plots, are interactive and if the user gazes on them the corresponding sphere displays additional information in the form of a text box: the engine identifier, the subsystem's name, along with
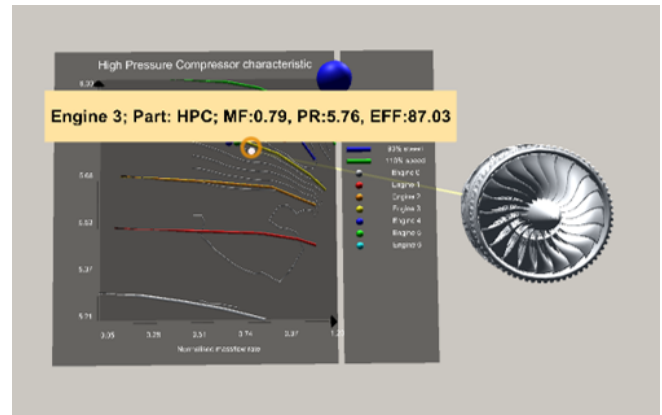

Figure 4. **A text box presenting additional information is displayed in response to the user gazing on one of the operating points on the HPC graph. Further, a line extending from the gaze-selected point connects it with the correlated engine.**

its inlet massflow (MF), pressure ratio (PR) and efficiency (EFF), and renders a color-coded line connecting the point with its corresponding aeroengine, as can be seen in Fig. 4. Legends in these three plots are set on the right side, so as not to occlude the information presented on the graphs.

The graphs are rendered semitransparent to mitigate possible occlusions effects [9]. They can be toggled to, for example, be either within the user's field of view or completely removed from it, with a press of a button on the left-hand menu, as can be seen in Fig. 5(a).

Although the data shown in these graphs is not representative of the performance of real engines, the choice of the performance metrics is. Our high-level aspiration through the pipeline detailed in this paper, is to offer engineers a

unique platform to visualize and make well-informed decisions based on the real-time working state of a fleet of aeroengine digital twins.

Interaction Methods

The interaction methods use both gaze and hand-tracking mechanisms. We use the gaze-tracking part of the *Unity VR Free Sample Pack* [30]. As it is simulated by estimating the gaze position and direction roughly in the center of the user's field of view, it does not require additional hardware. Gaze-tracking is used to inform the system which interactive object the user potentially wants to interact with. In turn, the object considered automatically highlights itself to signal to the user that it can be interacted with.

The user's gaze direction is simulated with an orange cross-hair as shown in Fig. 5(a). Bimanual gestural input is used to select and manipulate the interactive objects, such as the compressor characteristics plots (see Fig. 9) or the aeroengines models (see Fig. 1). All of these objects can be rotated along a chosen virtual axis, moved, and magnified or diminished in size using a set of simple hand-gestures as shown in Fig. 5. Some studies conducted using the Leap Motion sensor [27], suggests that having the possibility of using virtual hand representations can aid the user's in planning and execution of complex, multilevel actions [31]. We further conjecture that virtual hand representations allow the user to better assess object size. Prior work [10] has remarked that combining the gestural input with gaze tracking can enhance object manipulation task performance.

Interaction Modes

There are two main interaction modes, these are (1) the [engine] mode in which the user work with the assembled engine model that is treated as a whole, compacted, object and (2) the disassembly, that is, the [gear] mode, switched to by pressing the [gear] button on the left-hand menu in which the user deals with the engine parts independently (see Fig. 5(a)). If in the [gear] mode (see Fig. 5(a)), and the user selects a data point on the plot, it will highlight (i.e. turn light-green) and automatically select the corresponding engine's component—in this case one of the compressors (see Fig. 10), as presented in Fig. 3(a). If the same operation is invoked while the user operates in the [engine] mode (see Fig. 5(a)), then the corresponding points across all graphs will highlight (i.e. turn light-green) and the corresponding engine will be selected as well. Furthermore, if a part of the engine is selected, the associated point on the graphs will be selected as well. Hence, this cross-selection mechanism implements the well-known visualization technique called *linking & brushing*.

4. OBJECT MANIPULATION METHODS

As alluded to previously, the interactive objects, mainly the aeroengine CAD models and the compressors characteristics, can be directly manipulated by the user's hands. To support manipulation of the graphs we use the notion of *select-to-trigger-function objects* in which to manipulate the graph the user has to select it by activating one of its elements, for example, using the large sphere selector located in the top right corner of the plot. The user can also use gaze to select one of the markers placed on the graphs. The aeroengines models, and the plots as a whole, are examples of the *select-to-interact objects* technique.

Gestural Input

The system recognizes four different gestures. The user's hands are tracked using the Leap Motion sensor [27] attached to the front of the headset. The virtual representations of the hands (see Fig. 5), are shown in the user's field of view once they are present in the sensor's detection region. Gesture recognition was built using the Leap Motion SDK [27].

 prior study [32] suggests that using the *grasp* gesture instead of the *pinch* gesture may be more beneficial as it was favored by the study participants. However, we found that once users familiarized themselves with the pinch gesture, they were capable of manipulating the objects with ease.

There are four gestures that, depending on the mode in which the user was working in, invoke different actions as shown in Fig. 5. These gestures are enumerated below.

1. **Left-hand palms-up** invokes the menu attached to the user's left-hand palm.
2. **Pointing finger** used to single or double-press a button on the left-hand menu. The double pressing is required in case of the [reset] and [undo] buttons that once selected, invoke actions that cannot be reversed. Thus, the double-pressing requirement reassures that these buttons are not selected by mistake.
3. **Thumb-up** is used to release the user's handle over an object. If the user would like to manipulate another object and one is already selected, the user has to articulate this gesture in order to be able to select the desired object.
4. **Pinch** comes in two forms. First, to select an interactive object, the user gazes over it with a cross-hair and double-pinches it with either of the hands. The single-pinch gesture is used to manipulate the object.

Left-Hand Menu

The menu attached to the user's left-hand, will appear when the user turns the left-hand palm up as shown in Fig.5(a). The size and layout of the menu in terms of the amount of buttons horizontally and vertically, loosely follows the design guidelines prescribed in [33], who study the feasibility of using a menu attached to one of the user's palms. As the menu itself can be recalled on demand, it will not unnecessarily occlude the user's field of view. With the help of this menu, the user can, for instance, change the mode of operation, which in turn allows for new functionality to be associated with the same, small and constant set of basic gestures (see Fig.5). There are six buttons in total, split into two columns with three elements in each, as can be seen in Fig.5(a). These are:

1. [reset] double-pressed resets the visualization to its default state as observed by the user when starting the visualization for the first time.
2. [gear] single-pressed allows the user to individually interact with the sub-components of the engine models.
3. [undo] double-pressed restores the selected object to its default state, for example, automatically assembles and moves the previously dissembled engine into its default state and position.
4. [help] single-pressed reveals a text box containing user instructions.
5. [engine] single-pressed allows the user to manipulate the whole engine as if it would be a compact object.
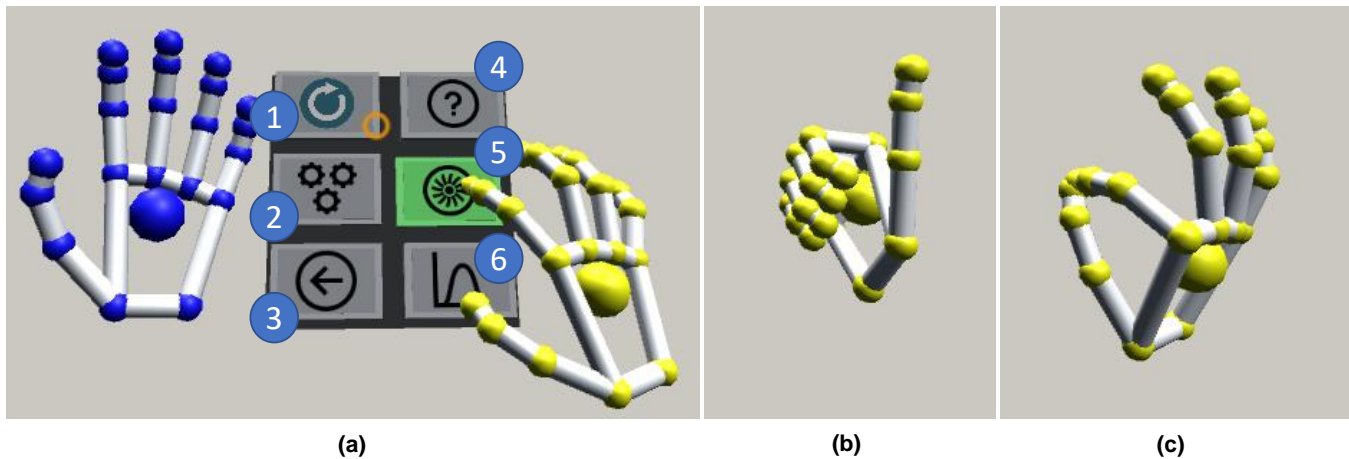6. [graph] single-pressed toggles the compressors characteristics graphs.

Figure 5. **The menu (a) opens up when the user makes the left-hand *palm-up gesture*. Then, by using the *pointing-finger gesture*, the user can invoke a series of actions: (1) double-press** $[reset]$ **to restart the visualization to its default settings; (2) single-press** $[gears]$ **to be able to take the engine model apart; (3) double-press** $[undo]$ **to reset the selected object to its default state; (4) single-press** $[help]$ **to show a brief description of the available options; (5) single-press** $[engine]$ **to manipulate a whole engine; (6) single-press** $[graph]$ **to toggle the graphs. The *thumb-up gesture* (b) can be used to deselect previously selected interactive objects. The *pinch gesture* (c) is used to select (double-pinch) and manipulate objects (grasp & hold). Icons by *Icons8* (`https://icons8.com`).**

Aeroengines Models Manipulation

While in the $[engine]$ mode, after selecting the model by gazing over it with a cross-hair and making a double-pinch gesture, there are three ways in which the user can manipulate the engine model. Moreover, if in the $[gear]$ mode, the user can dissemble the model and manipulate each sub-component the same way as the whole model, that is, rotate, resize and move it.

1. **Rotation**: The user can, by simultaneously using both hands to grasp (i.e. by using the pinch gesture) and rotate the model in 3D space along a chosen virtual axis. The engine rotation can be seen in Fig. 6.
2. **Resizing**: The user can, by simultaneously using both hands, grasp (i.e. by using the pinch gesture) the object and spread their hands apart or move them closer together to increase or decrease the models' sizes respectively, as shown in Fig. 7.
3. **Displacement**: The user can use one of the hands to grasp (i.e. by using the pinch gesture) and move the model into any position in 3D space.
4. **Disassembly**: When switched to the disassembly mode by pressing the $[gear]$ button on the left-hand menu as shown in Fig. 5(a), the user can pull the model apart to inspect all of its eleven subsystems. To do so, the user gazes on and grasps the parts one-by-one as if manipulating the whole engine model. For instance, in Fig. 8, the user has selected and pulled apart the outer casing of the engine, exposing all the different blade rows.

Plots Manipulation

The compressors characteristics can be manipulated in almost the same way as the engine models, that is, they can be (1) rotated, (2) re-sized or (3) displaced using the same interaction methods as in case of the aeroengines. However, prior to being able to do so, the user has to gaze on a selector (large, interactive sphere placed in the top-right corner of each plot; see Fig. 9) and make a double-pinch gesture to select it. This feature was incorporated because the graphs themselves are composed of multiple, smaller, interactive elements, that is, the points of operations of the engine's

compressors (see Fig. 2(e-f) and Fig. 9). This allows the user to differentiate between inspecting and working with those points or the entire graph. Examples of manipulation of the plots can be seen in Fig. 9.

5. INTERFACE EVALUATION

We carried out a small observational study with three domain-expert participants to distill further design insights from actual use of the system. This method is listed in the survey [34] of different techniques used to evaluate interactive visualizations in the research community and is suitable when domain expertise has considerable influence on effective use of the system, which precludes the recruitment of a large number of participants for a traditional A/B evaluation.

Study Participants

The system is designed for an expert audience that in their daily work are interacting with a very specialized, bespoke environment. As such, to test our system, we recruited a group of three expert-participants, hereafter referred to as P1–P3.

Participant 1 (P1): was a final year PhD student looking at the impact of leading-edge instrumentation in turbomachinery with Computational Fluid Dynamics (CFD). He holds an MEng degree in aerospace engineering where he focused on urban pollutant dispersion through wind tunnel modelling. He reported having limited exposure to hand-tracking systems and VR.

Participant 2 (P2): was a PhD student conducting research on the low pressure compressor (fan) interactions with the intake. He holds an MEng degrees in aeronautics. He reported to have limited experience with VR and some exposure to gestural input.

Participant 3 (P3): holds an MEng degree in aerospace engineering and a PhD in Computational Fluid Dynamics (CFD) of compressors. He also worked for a year on he-
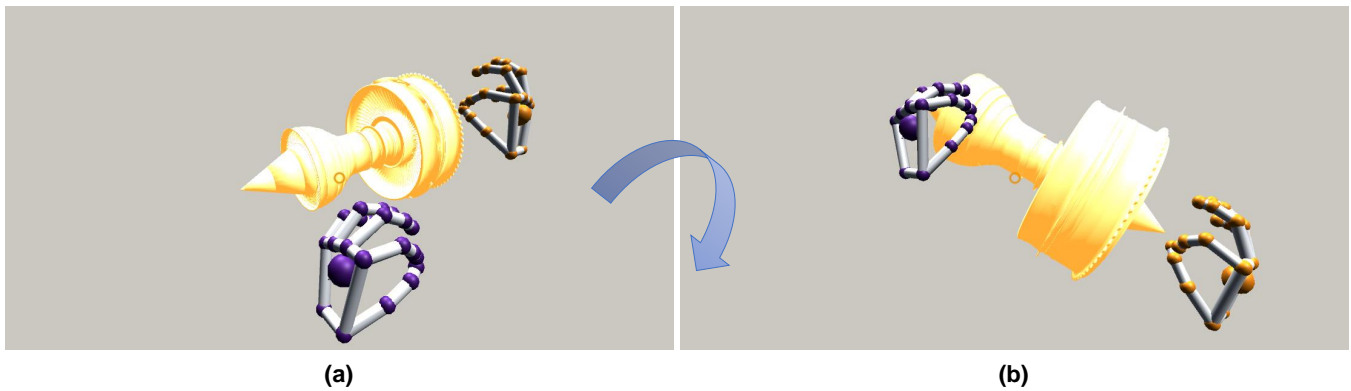
Figure 6. **The aeroengine CAD model rotated with the user's hand. While simultaneously making the pinch gesture with both hands and rotating one or both hands, the user can rotate the model around a chosen virtual axis.**
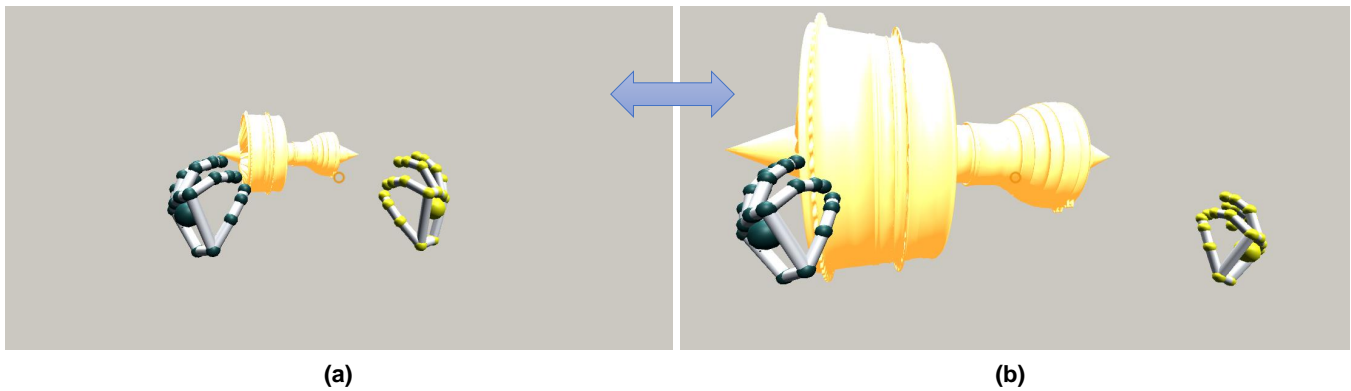

Figure 7. **The aeroengine CAD model magnified with the user's hands. While simultaneously making the pinch gesture with both hands and spreading them apart the user can increase the size of the model. When the user moves the hands closer the model will decrease in size.**
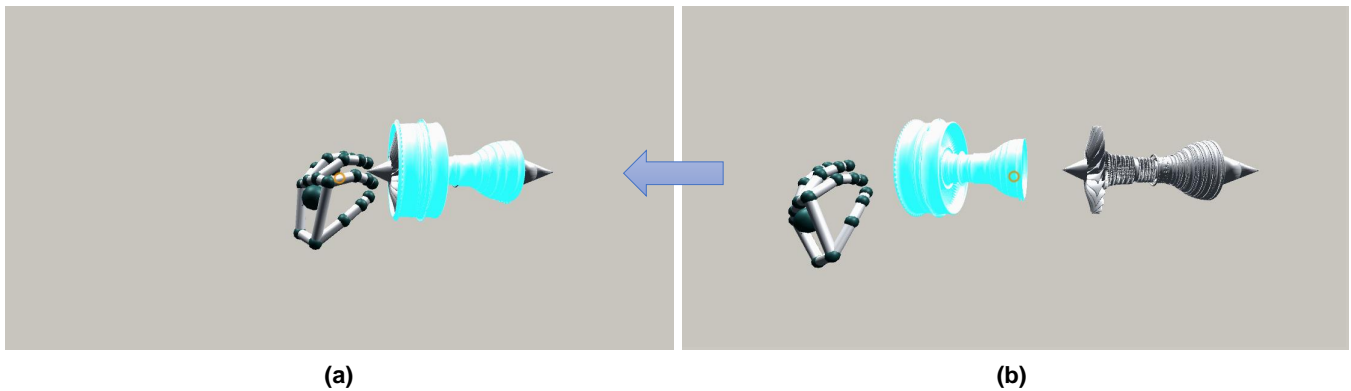

Figure 8. **When in the [gear] mode, users can interact with the specific part from engine. This figure shows the user moving the outer casing away from an engine.**

licopter fuselage aerodynamics, and six months on missile aerodynamics. He had no prior exposure to VR or hand-tracking systems.

Study Design

The study was carried out in two parts. First, the participants were all together shown a brief video of the system interaction capabilities. They were also given time to ask the questions and instructed to immediately stop the experiment if they felt any discomfort. Second, they were one-by-one asked to participate in the experimental phase of this study.

In the experimental phase participants were first asked to fill in the simulation sickness questionnaire (SSQ) [35] and then asked to carry out, in VR, a list of tasks. The tasks were delivered to them orally when the previous task was deemed to be finished to the satisfaction of the researcher who was always present when the participant was wearing the VR headset. Moreover, the participants were asked to think aloud and constantly discuss with the researcher what they were trying to do and what obstacles they were facing while doing it. They could also seek advice from the researcher if they did not know how to proceed further. In addition, the researcher would aid the participant if it was clear that they were stuck
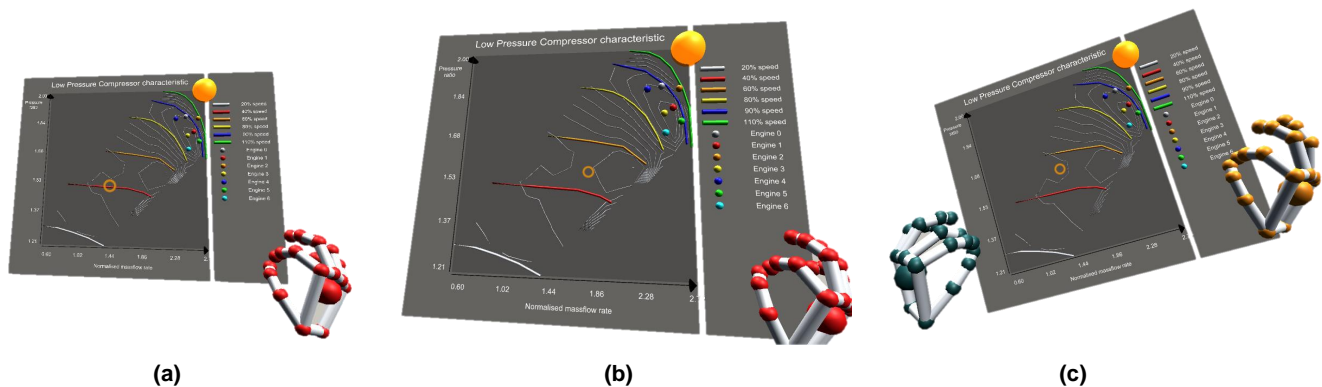
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Figure 9. **The user can move the graph (a–b) by activating its selection controller (orange sphere in the top right corner) and simultaneously grasping with a pinch gesture and moving the graph with any of the user's hands. The user can also rotate the activated graph (c) by making a pinch gesture and rotating the graph with both hands.**

as the researchers could observe what the participants were seeing on an accompanying computer screen.

Once all the tasks were finished, the participants were asked to fill in additional questionnaires and to comment on, and discuss with the researchers, their experience while using the system. These questionnaires were the Flow Short Scale (FSS) [36], NASA Task Load Index (NASA TLX) [37] and Igroup Presence Questionnaire (IPQ) [38].

Tasks

The group of tasks were designed in such a way that by carrying them out, the participants would have to use the full range of interaction techniques afforded by the system. They were also based on the authors' knowledge of which tasks would potentially be interesting to the domain-expert user. The tasks were split into three parts, based on the specific compressor subsystem that the user was interacting with; these are enumerated below.

1. Fan pressure ratio performance queries:
   (a) Identify which engine's fan is the closest to choke.
   (b) Identify which engine's fan is operating at 110% shaft speed.
2. IPC pressure ratio with geometry manipulation:
   (a) Isolate each subsystem from Engine 5. There are 11 subsystems in any engine.
   (b) Identify which engine's IPC is operating dangerously close to stall (relative).
   (c) Isolate the IPC in this engine and based on an inspection of the blades, can you determine the cause of this rather high pressure ratio? (Hint: Look at the first row).
3. HPC pressure ratio with efficiency contours:
   (a) At roughly what speed is Engine 3's HPC running at?
   (b) Based on the iso-contours of efficiency, state which engine's HPC is running at the highest efficiency (relative)?

The correct answers to these tasks require the user to closely inspect and manipulate both the engine models or the graphs. For instance, in the task 2(b), the participant is required to disassemble engine 6 and possibly manipulate the IPC component to observe that it is "physically" damaged and thus causing an increase in the pressure ratio and a decrease in the massflow rate—characteristic features of compressor stall.

Observations

These main points summarize the participants' behaviour:

- The participants were able to interact and manipulate the interactive objects smoothly after familiarizing themselves with the *pinch gesture* (see Fig. 5(c)). Grasping initially caused some confusion among all participants.
- Generally, the participants had no difficulty reading the information provided on the plots.
- The participants could successfully complete (see Table 1) the given tasks on their own, requiring only a few spoken suggestions from the observing researchers. However, participants sometimes did not identify the most efficient method possible given the system's functionality.

There are a range of reasons that can potentially explain why it took some time for the participants to learn how to properly make the *pinch gesture* (see Fig. 5(c)). First, participants were only once exposed to a brief video explaining the interaction methods before the experimental phase commenced. The impact of this *learning effect* is likely not consistent considering the participants' variable concentration and the duration between the video and the experiment. Second, all three participants were only vaguely familiar with gestural input systems and their inherent technical limitations. For instance, P1 often closed his fist when moving the hand away, which was sometimes recognized by the system as an execution of the *pinch gesture*. Further, the participants had to be reminded that in order for the sensor to properly track their executed gestures, their hands had to be located within the sensor tracking range which would be signaled with the virtual hand avatars present in the participants field of view (see Fig. 5–9).

Once the participants gained fluency in properly executing the *pinch gesture* they were able to easily work with the interactive objects. This is most likely due to the fact that the manipulation process, to some extent, reflects how such interaction would look like in the physical world. As the participants were asked to stand while carrying out the tasks, it was interesting to observe that all of them choose to walk in the limited space constrained by the HMD cables. This may be explained by the fact that, the engines models were spread horizontally in such a way that the participants could not see all the models and graphs at once (see Fig. 1 and Fig. 3).

During the study it was also observed that the participants seemed to be mildly confused by the relationships between the compressor characteristics and the engines (see Fig. 3).

For instance, P1 forgot that it was possible to select a point in the graph to simultaneously select a specific part in an engine (the LPC, IPC or HPC). Instead, to locate the engine of interest, he chose to follow the direction of the lines linking the points of operation on the graphs with the corresponding engine by moving the entire plot with him, and, in steps, placed it closer to the target engine. Then, after finding the corresponding engine, he disassembled it to be able to access the part (i.e. the broken IPC in Task 2(c) as seen in Fig. 10 and Fig. 11). After being told that he could select the part directly through the plot by switching to the [*gear*] mode (see Fig. 5(a)) he believed he could have performed better if he was familiar with the technique in advance.

Furthermore, the participants did not leverage all the available features. For instance, P3 commented that he often found having the plots visible in his field of view was annoying and he would prefer to have a features allowing him to hide them on demand. In fact, this functionality did exist in the system and could be easily accessed through the left-hand menu as show in Fig. 5(a).

Questionnaires Results

The results of the SSQ showed that P1 developed some slight symptoms of the simulation sickness (1/27 and 3/21 for nausea and oculo-motor strain respectively) whereas P1 and P2 experienced none.

The results of the NASA TLX (P1: 66/100; P2 66/100; and P3: 69/100) indicate that carrying out the given tasks required some effort from all three participants—a point that may be explained by the participants' low levels of prior exposure to both VR and gestural-input interaction methods. Moreover, the task partially relies on the participants domain knowledge which could also add to their cognitive load.

The results of the IPQ showed that the participants reported relatively high levels of the feeling of presence in the simulation with all the scores above 50% (P1: 3.64/7.0; P2:3.93/7.0; P3:3.57/7.0 respectively), which suggest positive engagement with the system.

The results of the FFS are given as two components: flow and anxiety levels. The participant reports are as follows. For participant P1: flow of 4.9/7 and anxiety of 2.5/7; P2: flow of 4.7/7 and anxiety of 2.5/7; and P3: flow of 3.4/7 and anxiety of 3.0/7. The relatively high levels of flow and low of anxiety across all the participants could indicate that they did not feel *out of place* when interacting with our visualization.

Tasks Results

The results of the task should be interpreted with caution as the participants were given unlimited time to finish the task and frequently sought the researchers help if they got stuck. Hence, even though the researchers put an emphasis on not leading the participant to answers, the answers are subject to bias. Regardless, it is worth noting that all participants managed to carry out the tasks correctly, with the exception of P1, who incorrectly identified engine 4 instead of engine 5 when using the LPC compressor characteristics plots. P1 remarked that he had no familiarity with the low pressure compressors. The correct answers to all the tasks are given below:

1. Fan pressure ratio performance queries:
  (a) The fan operating closest to choke is the fan on engine 5.

Task	P1	P2	P3
1(a)	engine 4	engine 5	engine 5
1(b)	engine's 2 LPC	engine's 2 LPC	engine's 2 LPC
2(a)	correct	correct	correct
2(b)	engine's 6 ICP	engine's 6 ICP	engine's 6 ICP
2(c)	correct	correct	correct
3(a)	80% speed	80% speed	80% speed
3(b)	engine's 1 HPC	engine's 1 HPC	engine's 1 HPC

Table 1. The table shows the tasks results for each of the three participants P1–P3. The cells with correct answers are marked with a light-green background whereas the only incorrect answer is marked with red background (i.e. answer to Task 1(a) given by P1). Whenever the task required visual inspection that the researcher had to deem complete, i.e. 2(a) and 2(c), the table indicates whether it was carried out with satisfying results (correct) or not (incorrect).

  (b) The fan on engine 2 is operating at 110% shaft speed.
2. IPC pressure ratio with geometry manipulation:
  (a) There are 11 subsystems in any engine as can be counted on the engine CAD model.
  (b) The IPC on engine 6 is operating dangerously close to stall.
  (c) The blades in the first row on the engine 6's IPC have been damaged (see Fig. 10(c)).
3. HPC pressure ratio with efficiency contours:
  (a) Engine 3's HPC is running at roughly 80% speed.
  (b) Based on the iso-contours of efficiency, engine 1's HPC is running at the highest efficiency (relative).

6. LIMITATIONS

Some limitations of the system functionality were imposed by the available data, system design and the hardware. For instance, the VR headset was connected to the supporting PC with USB and HDMI cables. In addition, the Leap Motion required separate USB connection. These cables restricted the range of participants' motion, as care must be taken to ensure that participants do not stumble or entangle themselves with the cables.

The participants chosen in our study were not pre-screened for symptoms of the color vision deficiency. In our system, being able to differentiate the colors is quite important, as we used the color-coding for both the selected engines as well as to color-code the data plotted on the graphs. In this respect, P1 mentioned that when the engine was highlighted, he could not clearly see the damaged blades on the IPC compressor in engine 6 without looking closely at the model.

7. DESIGN IMPLICATIONS

Here, we present a list of tentative design suggestions for designing of a VR system that use gestural input coupled with gaze tracking to interact with a complex, multi-element immersive visualization in VR. This list is guided by our own observations of the participants' behaviour while wearing the VR HMD as well as the participants' comments.

DI1: Training: Due to the novelty of the hand-tracking, as well as VR headsets, these technologies are not widely adapted in either mass-market, industry or academia. Hence, as observed in our study, the users must be provided with
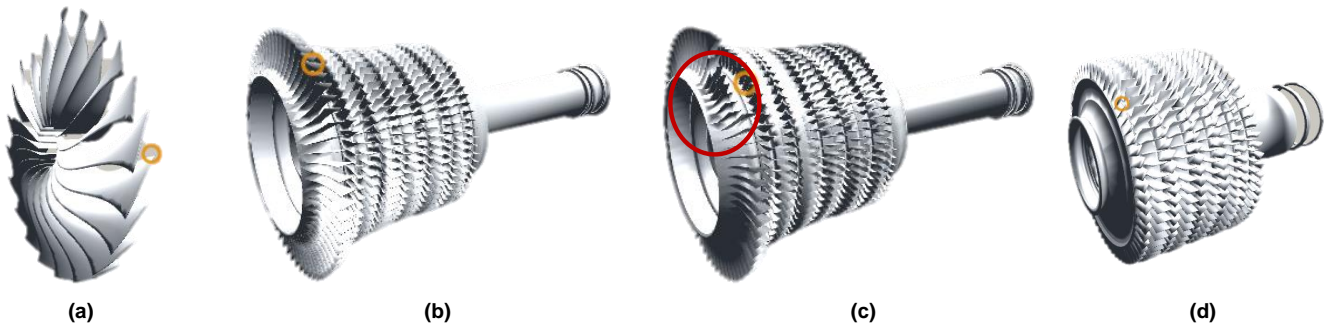
Figure 10. **The CAD models of the compressors: (a) low pressure compressor (LPC), (b-c) intermediate pressure compressor (IPC); (d) high pressure compressor (HPC). For the clarity, the scale of the aerengine parts is not preserved. The nominal IPC is shown in (b) along with the damaged engine (highlighted in red) in (d).**
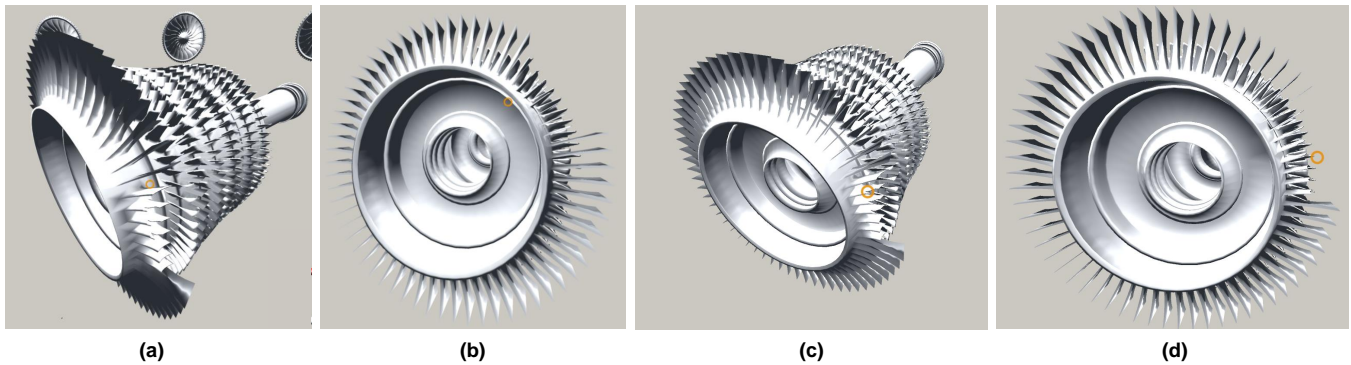

Figure 11. **The CAD model of the faulty intermediate pressure compressor (IPC) seen from different perspectives after being rescaled and rotated by the user.**

training in how to interact with the system using gestural input.

DI2: Object Placement: In general, placing objects, in this case the aeroengine models (see Fig. 1), around the user in the horizontal plane was potentially better than using the vertical plane. However, to aid the users in finding objects outside of their field of view, additional navigational indicators may need to be developed and tested. P2 suggested that some form of a conveyor belt that would rotate the engines in his field of view might be helpful, instead of having to repositioning himself in 3D space. P3 pointed out the separation between engines and graphs may cause confusion to participants. He also suggested that only after an engine or a part is selected, should the plots become visible.

DI3: Complex Graphs: Following the suggestion in [14] and the comments of P3, the use of 3D graphs could be better utilized. For instance, the iso-contour plots, such as the ones used in our study, could potentially be more beneficial to the users if the contour-lines would extend from the plot, forming a 3D-like structure. Then, given the plots' rotation and re-sizing capabilities, it would be easy for the user to spot anomalies and outliers.

DI4: Object Manipulation: Prior related research [31], suggests that bimanual manipulation of objects is a very promising and favorable way of interacting with CAD and other types of 3D models embedded in a VR environment. In practice, the gaze tracking system caused some trouble for P1 when trying to observe details of the damaged engine as the object had reduced contrast when highlighted by the gaze cross-hair. P1 suggested a feature to deactivate the gaze

tracking-based highlighting.

8. DISCUSSION

Given the limitations of both hardware and the study design, to some extent imposed by the difficulty in recruiting a large number domain-expert participants, the results of the experimental study should be interpreted with caution. This small formative study was designed to help us identify initial usability problems, spot potential improvements, and gain insights into aerospace VR design interaction capabilities. It does, however, allow us to trim the vast design space and to guide further design efforts in this area.

One of the most interesting elements of the visualization was the possibility of disassembling the CAD aeroengine model into its composite subsystems, which could be independently manipulated and inspected in the same way as the entire engine. Coupling these with the compressor characteristic plots allowed the participants to carry out a complex, multi-level tasks in VR. Although not completely satisfied with our system as stated in the remarks made by the participants, they all managed to correctly finish the given tasks. We believe, that to some extent, their dissatisfaction may stem from the short duration of the training provided in a form of video screened before the experiment commenced. Most likely, if given a greater familiarization period whilst immersed in the VR environment, for example, by providing a prior training phase, the participants would be able to carry out the task more favorably, leveraging all the functionality that the system has to offer, such as, an ability to turn on and off the plots on demand. Also, as mentioned previously, the

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participants could potentially quickly accustom themselves with the *pinch gesture* which in turn would allow them rapidly grasp and manipulate objects.

9. CONCLUSIONS

In this work we introduced an interactive, immersive system for the simultaneous visualization of the performance of a fleet of aeroengines in VR. The first iteration of the system, named *AeroVR: Aeronautics Virtual Reality Environment* was first presented in [39]. The version discussed in this paper uses 3D geometric computer-aided design (CAD) models of the engines paired with compressor characteristics maps plotting the pressure ratio and efficiency as a function of shaft speed and inlet flow capacity of the low (LPC), intermediate (IPC) and high pressure compressors (HPC) for each engine. Superimposed on these maps are the true performance of each engine, obtained through real-time sensors. This allows the user to promptly diagnose and spot potential issues with the engine sub-systems across the entire fleet.

As discussed earlier, the selection of an appropriate interaction technique is one of the key ingredients of such a system. Here, we explored how can we leverage interaction methods facilitated by gaze-tracking coupled with hand-tracking achieved via an additional sensor attached in front of the VR headset, with no need for the user to hold a controller. We undertook an observational study with a small number of domain-experts to distill a list of design implications relating to the development of our VR visual analytics platform. The analysis of the results from this formative study allowed us to trim the design space and to guide further design efforts in this area.

There is a number of potential avenues for future research. One of them concerns the 2D graphs. For example, P3 commented that representing a 2D graph in 3D space had no significant advantages over that in 2D space. He suggested allowing multiple dimensions which could make better use of the VR environment. As discussed in *DI3: Complex Graphs*, we could, for instance, extend the iso-contour lines into the Z-plane in the plot's local coordinate system to form a 3D-like structure. This maybe particularly useful as outlier points, such as the one the participants had to find in Task 3(b), could more easily be spotted as they would be on top of such plot if rotated along the X-axis. In addition, such plots could be easily rotated using our bimanual manipulation method.

It may also be interesting to investigate the different alignment of the aeroengine models. For instance, as proposed by P2, we could include the functionality similar to one offered by a conveyor belt. In this case we could either place the engines on a conveyor belt, or rotate the engines on an arc using the *swipe gesture*.

These potential research directions represent future work and will be investigated and tested in a series of controlled experiments. These investigations will permit us to develop our promising gestural-based input method as means of interaction for 3D immersive analytics.

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