Sci-fi Miners: a virtual reality journey to the nanocluster scale

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ABSTRACT

In this publication, we present the result of an artistic residency occurred mainly at the International Iberian Nanotechnology Laboratory, within the framework of STARTS European Commission initiative (Science, Technology, and Arts), exploring how, with the help of scientific advances in nanotechnology and artificial intelligence, a new generation of nanoclusters are replacing critical natural resources becoming very rare on planet earth. 'Sci-fi miners' is an audio-visual and virtual reality work related to the possibilities generated by the nanotechnological advances in the research of critical materials' replacement, by improved nanoparticle control. Those natural resources, critical metals, especially rare platinum group metals (PMGs), are essential and used for heterogeneous and electrochemical catalysis. As 90% of things (goods) we use in our societies is produced by catalysis, humans depend strongly on these natural resources. Currently, many countries are profoundly dependent on the mining industry to obtain these materials, relevant for fuel cells, storage of renewable energy, and for pollutant emissions control. Although this article approaches an immensely sophisticated technology, scientific bases related to the generation of new nanoclusters will not be covered, but rather the imaginative and practical approach in the creative process of producing a virtual reality artistic performance. We will cover creative work inspired in this research and focus this publication in the development of a series of visualizations, observations, reconstructions at the nanoscale, virtual reality developments, and the artistic results that emerged from the interactions between scientists' teams and an artist in residence.

CCS CONCEPTS

• Virtual reality • Scientific visualization • Interactive simulation • Media arts

KEYWORDS

Nanotechnology, Nanoclusters, Virtual Reality, Performance, Media Art

1 Introduction

For centuries, artists have made clever use of materials science and technology, creating and finding increased use of technology as a medium of artistic expression, and as a vehicle for communicating scientific advances to a broader audience [1]. Today it is recognized that, in addition to scientific and technological skills, creativity and co-creation are vital to allow innovation to happen and be valuable for society. With alternative methods of exploration and critical viewpoints on technology, artists can contribute to innovation and technology that is human-centered and adapted for society. Arts act as a catalyst for the conversion of science and technology knowledge into novel ideas and approaches in society [2]. Recognizing the importance of these trends, the European Commission launched the STARTS initiative to promote the inclusion of artists in innovation projects. In this publication, we will describe the process of an artistic residency occurred, between 2018 and 2019, in the STARTS Residencies program, called 'Sci-fi Miners'[3][4], within the EU CritCat project [5]. CritCat means 'Critical Catalysts', where researchers from a large European consortium [6] are developing new catalyst nanoparticles from Earth-abundant materials for hydrogen-based clean energy applications. Platinum group metals (ruthenium, rhodium, palladium, iridium, and platinum) have similar physical and chemical properties, tend to be found together, and are commonly associated with ores of nickel and copper. PGMs are generally derived from the same types of ore deposit in which they occur together, commonly in the same mineral phases. For this reason, they are classed as co-products, because they must be mined together. They rarely occur in native form [7]. The extraction of those materials is currently made by the mining industry, in deep caves located in a small number of regions in the world, in very low concentrations, especially in South Africa. Nowadays, we can obtain a few grams of platinum per ton of rock, and the extraction process is expensive and long, becoming more costly as these natural resources are becoming scarce [8]. There are indeed studies and plans to extract those resources in outer space, in the moon and asteroids, to fulfill the need of current consumer and economic trends on Earth [9][10].

The reason we are naming this work 'Sci-fi Miners' is purely conceptual, imaginative, reminding brave explorers discovering and facing unknown worlds, looking for new spheres of research, and trying to solve human problems, as the alchemists of medieval

Europe that employed water and fire to change the optical, chemical, and physical properties of materials [1]. Catalysis is the process of increasing the rate of a chemical reaction by adding a substance known as a catalyst, which is not consumed in the reaction and can act continually and repeatedly. 18th-century chemistry scientists that worked in catalysis were Eilhard Mitscherlich, whose contributions to classical chemistry were indispensable, and referred to it as 'contact processes' [11], and Johann Wolfgang Döbereiner, who spoke of 'contact action' [12][13]. In fact, this is the literal definition of Interface, a wide term used in the media arts for different proposes. Interface (in the physical sciences) is a boundary between two spatial regions occupied by different matter, or by matter in different physical states.

In this paper, we present artistic practices associated with the course of the residency and the in-between multi-disciplinary work at INL and Aalto University. We will present an introduction to some interesting approaches between nanotechnology and the media arts, and we will describe the artistic residency and the developments related to the creation of a virtual reality performance at the nanoscale.

2 Nanotechnology and Media Art

Imagine one millimeter … now, divide it by one million. That is one nanometer. This is an incredibly small scale. The conceptual underpinnings of nanotechnologies were first laid out in 1959 by the physicist Richard Feynman, in his lecture 'There's plenty of room at the bottom' [14]. Feynman explored the possibility of manipulating material at the scale of individual atoms and molecules, imagining the whole of the Encyclopaedia Britannica written on the head of a pin and foreseeing the increasing ability to examine and control matter at the nanoscale [15]. The nanotechnology term was coined by Tokyo University of Science Professor Norio Taniguchi describing semiconductor processes [16]. Implications of using nanotechnology are present in everyday life, and it plays a significant role in our life and society. Robert Fludd, 17th-century alchemist Robert, imagined the Sun as gold and printed it by using gold nanoparticles [1]. In 81 came a great breakthrough: the invention of the scanning tunneling microscope (STM). Gerd Binnig and Heinrich Rohrer, the inventors of the STM, wrote that when they first captured images of a surface of silicon atoms [17]. In 2005, artistic couple Christa Sommerer and Laurent Mignonneau presented Nano-Scape a work to let visitors intuitively experience aspects of nanotechnology by interacting with invisible self- organizing atoms through a magnetic force feedback interface [18]. In the same year, artists Victoria Vesna and James Gimzewski shifted the idea of nanotechnology from a mechanistic vision of the 20th century to a sensorial and ephemeral one, demonstrating compelling results when joining groups of scientists and artists outside the academic walls, and providing a vision that we are all, from the bottom up, molecular in origin [19]. Imagery is playing an important role as nanotechnology matures by making the invisible world of the nanoscale comprehensible and familiar [20]. For Hawkins and Straughan, the nano in its refiguring of our physical and physiological constitutions opens up the possibilities for a reframing of geographical questions, empirical objects, and conditions by thinking big thoughts through infinitely small things [21]. Astrophysicists and nanoscientists, through visualized algorithms, receive pictures out of the depths of the macro-cosmos, and the micro-cosmos, respectively, and visualizing complex ideas, structures, and systems, is a challenge we face today. Life sciences rely heavily on images to demonstrate the performance of models that otherwise could hardly be communicated or even thought of [22]. Previous work was developed at the Micro and Nano fabrication department at INL, where a series of visualizations to characterize nanopillar structures was created, and ended in a audio-visual performance presented at the its 10th Anniversary, in Braga [23].

3 The CritCat project and the context of this work

The goal of CritCat project is to improve size, shape, and surface structure control of the tailored nanoparticle catalysts via novel cluster/nanoparticle synthesis techniques that can produce samples of unrivaled quality, aiming a high conversion and improved selectivity [24]. The research includes up-scaling of the size-selected catalyst nanoparticle samples up to macroscopic quantities, which will enable them to be included as basic technological components for realistic catalyst systems [5]. The average size of a nanocluster is between 1 to 4 nanometers. Nanoclusters consist of a small number of atoms, at most in the tens [25]. These nanoclusters can be composed either of a single or of multiple elements. Clusters have been shown to exhibit "magic numbers" corresponding to closed shells of atoms or of electrons with particular stability. Clusters also exhibit physical and chemical properties which differ drastically from the corresponding individual atoms or bulk solids and depend acutely on cluster nuclearity – especially in the "non-scalable" regime [26].

The project described in this publication is called 'Sci-Fi Miners', an artistic residency happening at CritCat partners a) the Nanochemistry Research Group [27] at INL (International Iberian Nanotechnology Laboratory, located in Braga, Portugal, led by Doctor Yury Kolen'Ko and b) the Surfaces and Interfaces at the Nanoscale (SIN) group [28], located in Aalto University, in Helsinki, led by Doctor Adam Foster. The artist visited both labs in the course of the residency.

4 The artistic residency concept

Humans depend strongly on catalysis. And catalysis is dependent on Platinum Group Metals. PGM belongs to the so-called Critical Raw Materials – becoming rare on earth [29]. PMGs provides clean and sustainable energy technologies, an important value for us and future generations. Earth is immensely large, but as these materials are only found underground, hard to obtain, we will soon enter the risk of supply in the next decades. We should worry about natural resources running out, and these rare materials should be replaced by something abundant on the Earth. This is the aim of CritCat project. Nowadays we can extract a few grams of platinum per ton of rock. Latest EU reports say that in 15 years, platinum group metals will not be sufficient to fulfill current society consumer trends [7]. Urgency is the word we find for this research. That is why this work's name is Sci-fi Miners (referring to the researchers), once the extraction of those rare materials is currently made by the mining industry, large economic groups, in deep caves located in a small number of regions in the world, in very low concentrations. Also, resource extraction is responsible for half the world's carbon emissions [30].

As in the proposed concept, Sci-fi Miners are the brave researchers finding alternative methodologies to substitute PMGs, using earth-abundant resources. Moreover, this is not done with large construction infrastructural digging machines in the deepest caves, but in the cleanroom labs, at the nano and atomic scale. Researchers are exploring Nanotechnology and Artificial Intelligence to do it. In the past months, the artist in residence has been interacting with researchers from CritCat project partners, talking with them, observing their current research, making questions, looking at images at the nanoscale, materials, data, and publications, to develop visual interactive simulations and interfaces. Sci-Fi Miners is an artistic exploration of how, with the help of scientific advances in nanotechnology and AI, we will substitute critical rare raw materials on Earth, intending to let the public know how significant this research is for humankind and the sustainability of our planet.

5 Development of Sci-fi Miners

Faced with CritCat technology and after long conversations with scientists, the process of developing an artistic idea and its materialization took some time: 6 months. Initially, the artist verified several images previously obtained by microscopy (scanning and transmission and electron microscopy) at the CritCat project partner Forschungszentrum Julich Gmbh, Germany**.** Then, he began by developing computer codes in order to extract visual information about microscopy observations (Fig 1), like color and shape morphology or concentration, observing its complexity. He also developed a series of data visualizations, after some interactions with the team, who had the desire of representing, in a single interface, several chemical formulas reactions with the option of changing parameters in real-time, for example, the temperature in the catalytic process, a relevant parameter in the characterization of results [31]. The artist developed a visual scenario with several interactive sliders, using open-source development software Processing [32], in order to achieve those visualizations (Fig. 2), demonstrating how the catalytic process is a dynamic and complex phenomenon, depending on many variables and circumstances.

This process was interactive between the scientists and the artist, and the first developments happened in order to the artist appropriate the research in course. It was also an important step in establishing confidence with the scientific team. Interdisciplinarity doesn't start with people asking what is their part of the cake but people bringing the cake to the table. It seems banal, but in reality, it is quite difficult [33].

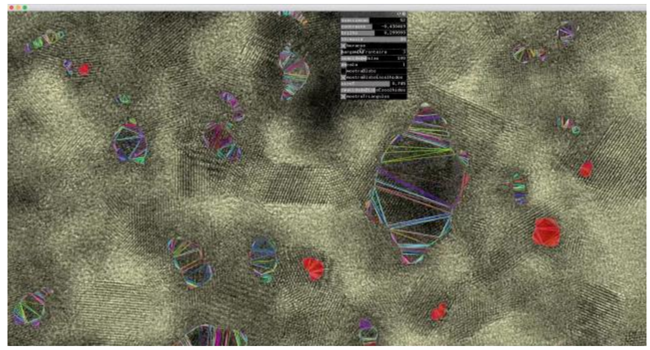


Figure 1: first computer vision approaches to the microscopy observations.

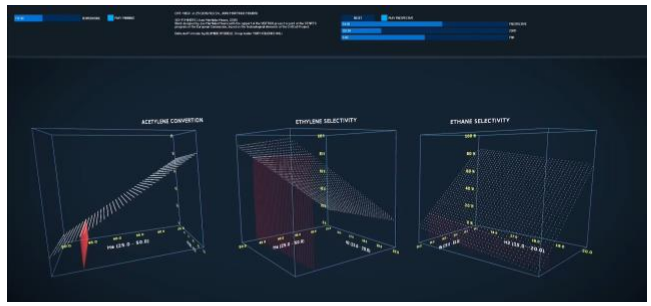


Figure 2: visualization C2H2Conversions. Visual software created by the artist, supervised by the researchers' team, in the course of the residency.

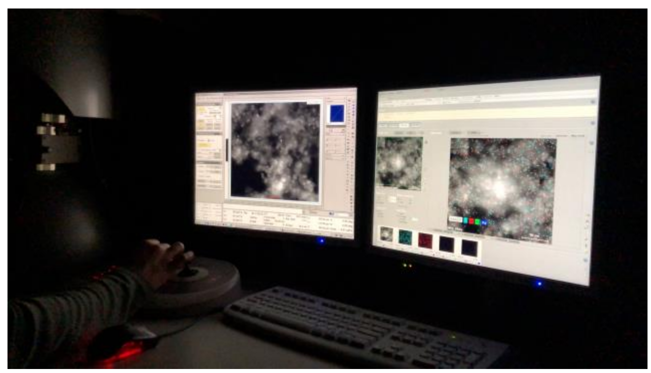


Figure 3: observing nanoclusters in the TEM microscope at INL.

The artist also had the unique opportunity to observe materials using one of the most advanced microscopy instruments in the world, the TITAN microscope [34], located at INL facilities, in Braga (Fig. 3), so powerful it can probe the spaces between atoms. That is an incredible asset to any media artist working in the field of art and sciences. At that moment, and after observing atomic-scale images, a point of no return was established in the course of the residency. The artist wanted to teleport people to that space, so small, so inaccessible, unleashing imaginaries that only the arts could empower. With the help of Microscopist Doctor Alec Lagrow, a series of images were obtained following very precise coordinates in order to connect visual elements into a virtual space. White small dots represent nanoclusters inside a sample of Pt NPs on cerium with 5% Pt weight loading. Colored dots in the monitor represent quantities of different atomic elements in the space. With a series of images from different scales and positions, an equirectangular 360 scenario was reconstructed and perfectly positioned around a participant in virtual reality (Fig 4).

Figure 4: a first experience in virtual reality with TEM observations.

Because TEM images are flat, at this moment, no sense of depth was experienced, and depth is a crucial element for virtual reality scenarios. After INL first series of observations at the TEM instrument, the artist visited a CritCat project partner in Aalto University, the SIN group (Surfaces and Interfaces at the Nanoscale) and became aware of the new models of nanoclusters that were being generated from artificial intelligence processes, and DFT (Dense Functional theory). DFT is a computational quantum mechanical modeling method used in physics, chemistry, and materials science to investigate the electronic structure of many-body systems, in particular atoms, molecules[35]. Those theories were initiated in the 20s by Llewellyn Hilleth Thomas, a British physicist, and applied mathematician. Thomas is best known for his contributions to atomic physics and solid-state physics [36]. DFT is used to compute ground-state electronic properties of large and disordered systems at the level of state-of-the-art electronic structure calculations [37]. From an artist perspective, restricted to a short residency timeline, these concepts were very complex, but at the same time, provided imaginary for creation. It would be impossible to create a real-time virtual reality precise system that would calculate the movement of atoms around nano-clusters since the computation needed to create these behaviors is so big that some algorithms could take much time (years) to be executed [31]. Those algorithms produce data, also feed by data, and as our ability to generate information far exceeds our capacity to understand it [38], visualization plays a significant role in science, education, but also in arts, as in contrast to much of the scientific method, visualization is often subjective and relies heavily on personal taste [20].

For this reason, the artist, after several conversations with the SIN group scientists, proposed the creation of a cinematic scenario that could offer anyone the opportunity to closely observe attractional behaviors at the CritCat nanocluster scale, using computed physics simulations commonly used in game engines. A midpoint compromise between accuracy and narrative, between the real and the imaginary, between facts and storytelling, was established. The goal of this artistic residency was to tell a story, spread awareness, to teleport participants to imagined unknown worlds. Artist's motivations and creations are new and different compared with the ones in the scientific visualization community, and neutral analysis is not the only important task in life [39]. Moreover, having an artist in the team was a bonus, approaching a possible solution to one of the major problems in the area of scientific visualization: the representation of error or uncertainty [40]. It is also important to refer that artists have some advantages in geometric reasoning, due to their training in the visual arts [41], and even their freedom to risk, a favorable asset, if well-coordinated, to join research teams.

As a starting point, a set of data files with XYZ atomic positions coordinates was given to the artist, and a first visual simulation was developed in Helsinki, an initial attempt to produce real-time visual scenarios to be included in the artwork. In the data, specific white represented points represent absorption sites, where molecule attraction happens around nanoclusters (Fig 5). Those molecules, when attracted to the nanocluster's absorption sites, join other molecules, and the catalytic process happens.

Figure 5: Nanoclusters generated at Aalto University. Visualization software developed by the artist.

The artist defined a journey distance range for the nano-space scale travel, which began in the millimeter scale (1mm) (Fig 6) and would end up on the scale of one nanometer (1nm), using virtual reality technologies. Artists working in any given medium seek to exploit the specific qualities of that medium in their work. Virtual reality has many features that combine to make it a truly unique medium, as the ability to manipulate the sense of time and space [42]. It would be an interesting step in the project, and could also be representative for the general public, also to gain awareness to the goals of this research, as an important value for us and future generations.

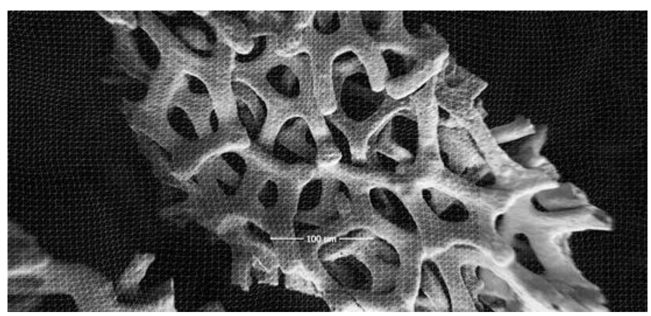


Figure 6: Nanoparticle foam to produce clean hydrogen fuel. Observed with a Scanning Electron Microscope.

After Helsinki, at INL clean room facilities in Braga, nanoparticle foam to produce clean hydrogen was observed at the SEM instrument (Scanning Electron Microscope). A series of observations, from different angles, were conducted in order to reconstruct the sample in 3D, using photogrammetry, a process of obtaining reliable information about physical objects and the environment through processes of recording, measuring and interpreting photographic images [43]. Photogrammetry is most reliable in colored series of images, to better fit corresponding matched points in image sequences. Because SEM images are grayscale, we recorded a considerable number of images, more than a thousand, from different angles to achieve enough data to reconstruct a tridimensional model. The reconstruction process required several steps of observation with rotation and tilt operations in the SEM, with very small step changes over time. The generated three-dimensional model contained 20 million vertices, which, for performance reasons, were reduced to 5 million. Instead of putting the reconstructed 3d object with faces, we chose to use only the vertex points in the cyberspace, sometimes connected by low opacity lines (Figs. 7, 8). In this way, we achieved a framerate rate of more than 90fps in virtual reality, with 5 million points to simulate the nanoscale, using GPU instantiation.

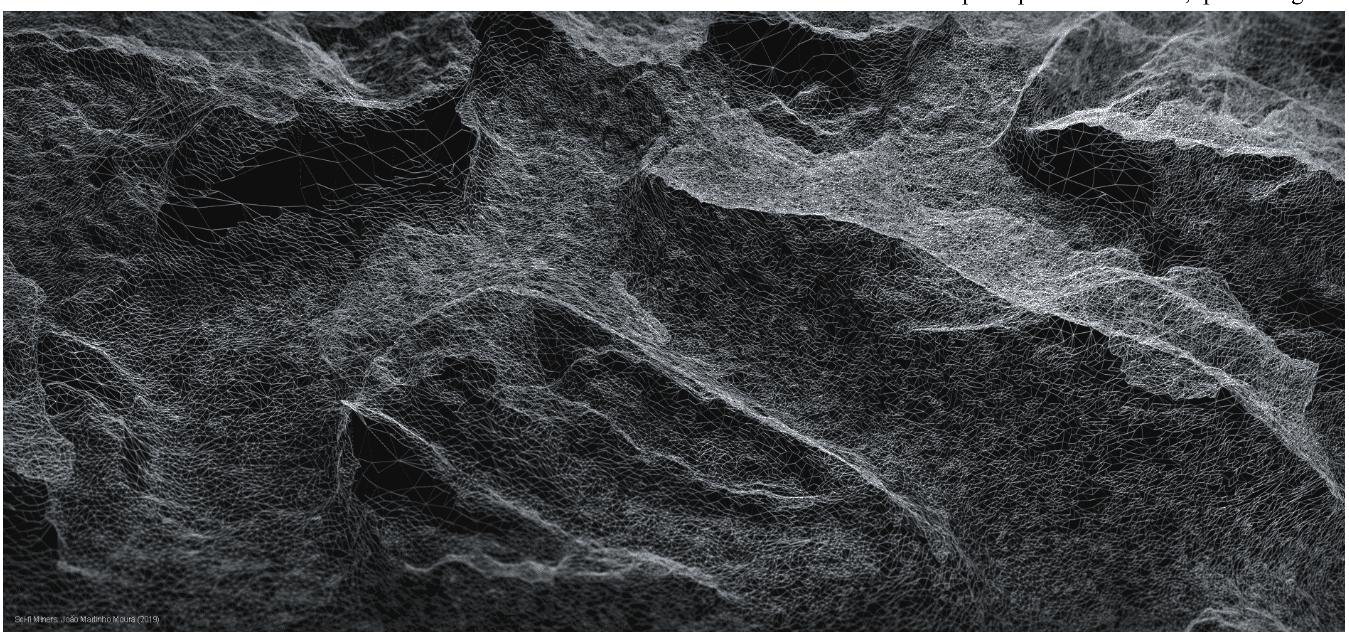


Figure 7: Generated reconstruction calculated by SEM microscopy observations at INL cleanroom, representing nanoparticle foam to produce clean hydrogen fuel. Approximate scale: 10µm.

The graphical hardware system was composed in a recent PC machine with dual 1080ti Nvidia system. We considered this first environment a perfect setting to position the viewer in the middle of the sample. Virtual reality requires significant graphical processing since the rendering happens in the HDM for both eyes. We used the HTC Vive Pro HMD device, which is one of the highest resolution HDMs in the consumer market.

Figure 8: "You're now at the nano space", virtual reality experience. Dots represent real observed nanoparticle foam (approximate scale: 5µm). The participant is teleported to the nanoscale, in virtual reality, a journey to the 1nm nanocluster atomic dimension.

We had the perfect stage for the first step of a journey that would start on the 1mm scale. Science now requires more from visualization than ever, using new forms of display visual information [40]. We also privilege spacial information, establishing connections from different scales over time. We based our visualization in the principle of reduction, presenting the participant with the fundamental elements for a better understanding of the phenomena [44]. The experience of reconstructing 3D models from direct observation was a very important step in the residency process. Image observations obtained by SEM or TEM are always bi-dimensional, and the fact that they were converted into three dimensions offered the possibility of being able to climb them to a size that could be contemplated by participants. Figure 7 shows a beautiful frame of a sequence, in slow motion, a landscape representing real matter, and in which we could navigate, appreciating micro-mountains and valleys. Extracted dots from photogrammetry were connected by lines, providing a volumetric notion of space. The CritCat project has two implications: a) theoretical driven (using Artificial Intelligence) to predict new nanoclusters, and b) experimental – to test new materials composition and size geometry.

Figure 9 shows the CritCat Nanoclusters. In the left side, we present computational generated model at the SIN group, in the right, we show direct observation of a real sample, at INL. These clusters are composed of atoms (Fig 10), having absorption sites that attract molecules. As different molecules collide with the cluster, they sit in the absorption sites, and when colliding with other types of molecules, a reaction happens. Figure 10 shows a VR scenario where computed CritCat nanoclusters are displayed to the participant, at a scale of one to one.

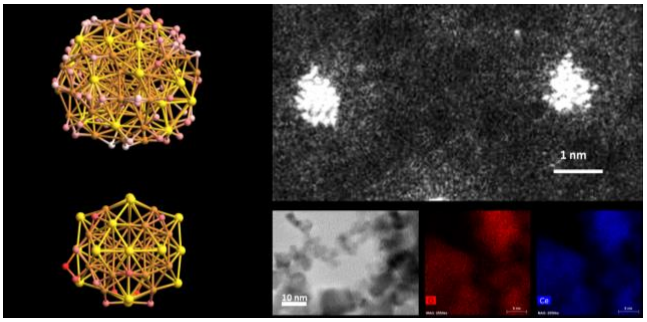


Figure 9: CritCat Nanoclusters. Left: computational representation by SIN group, at Aalto University. Right: observed with Microscopy at INL.

At this point, the participant is teleported to the scale of the nanometer unit, something that can only happen in virtual reality environments. Figure 11 shows the catalytic process, where a series of molecules, represented by lighted spheres, collide and bounce into three nanoclusters sited in the surface. A conceptual scenario of the catalytic process, happening in slow motion, in a virtual reality simulation, designed for the general public, a cinematic experience, important for a better understanding of the research goals in CritCat.

Figure 10: Virtual reality interactions.

This simulation is merely demonstrative of the concept, as an artistic perspective. Although not supported by precise computational rules from the point of atomic behaviors, it gave participants the real possibility to visualize, on a large scale, the nanoclusters models that were being computationally generated. In the simulation, there is an ambient sound, created by the artist, and inspired by the sounds he heard while he remained in the cleanroom and operating the scanning electron microscope.

Figure 11: cinematic environment presented to the participants.

During the artistic residency, there was a very special moment in the CritCat project. A meeting was held with senior researchers from around the world, the annual Critical Raw Materials Reduction in Catalysis Workshop [45], and the artist was invited to present the progress of his work at the conference, in a more informal moment, after various speeches and research presentations. Virtual reality is well known for being an individualized experience, hard to demonstrate to large audiences, as each user can take a few minutes participating in the immersive experience. In this sense, the artist proposed a different approach: the presentation of an audio-visual performance on stage. In this performance, audio-visual moments that contained all the produced material were presented, and a special moment occurred: the artist, in the middle of the stage, donned a VR helmet, and made the journey to the nanocluster scale with the audience.

6 Virtual Reality, and a performance on stage

We have been to the moon; we have human beings living on the international space station, we have already sent robots to Mars, and we will certainly be there in the next years. It is something we humans can do physically. The journeys of humanity into new macro spaces are real and broadens our horizons as entities in our universe. In addition to the macro space, there are numerous spaces in the micro space, beautiful landscapes, far below the millimeter scale, in which we can never physically be, because of the simple and real fact that they are very small physically spaces unreachable to a human being. However, since the 1960s, we have been developing technology to support the idea of teleportation to these unfamiliar spaces. Virtual Reality (VR) has the unique power to teleport us to wonderful and unprecedented worlds, transforming space, time and matter [immaterial], and fusing time and space into a single concept [46]. In the 60s, Morton Heilig created the Sensorama apparatus, a machine that is one of the earliest known examples of immersive, multi-sensory technology [47][48]. Ivan Sutherland, in his paper from 1965 entitled ‘The ultimate display’ reinforces the idea of a display connected to a digital computer that gives us a chance to gain familiarity with concepts not realizable in the physical world, as a looking glass into a mathematical wonderland [49]. In the 80’s, Scott Fisher, founder and director of the Virtual Environment Workstation Project (VIEW) at NASA's, worked in interesting prototypes to help users, like pilots, make better estimates of spatial relationships on 2D displays, and developed special head-mounted displays (HMDs) at the Ames Research Center to simulate space activities [50].

Figure 12: João Martinho Moura, performing at INL main auditorium in April 2019.

For the performance on stage, the artist developed techniques that showed, in a large projection, the images he saw while in immersive mode (Fig 12). To do this, he used the concept of multiple virtual cameras, which showed the audience several perspectives of what was happening. If we took a direct video sample of the helmet image, the normal vibrations of the head would be very noticeable by the public. Therefore, to have a more stable image, a virtual camera was placed behind the artist.

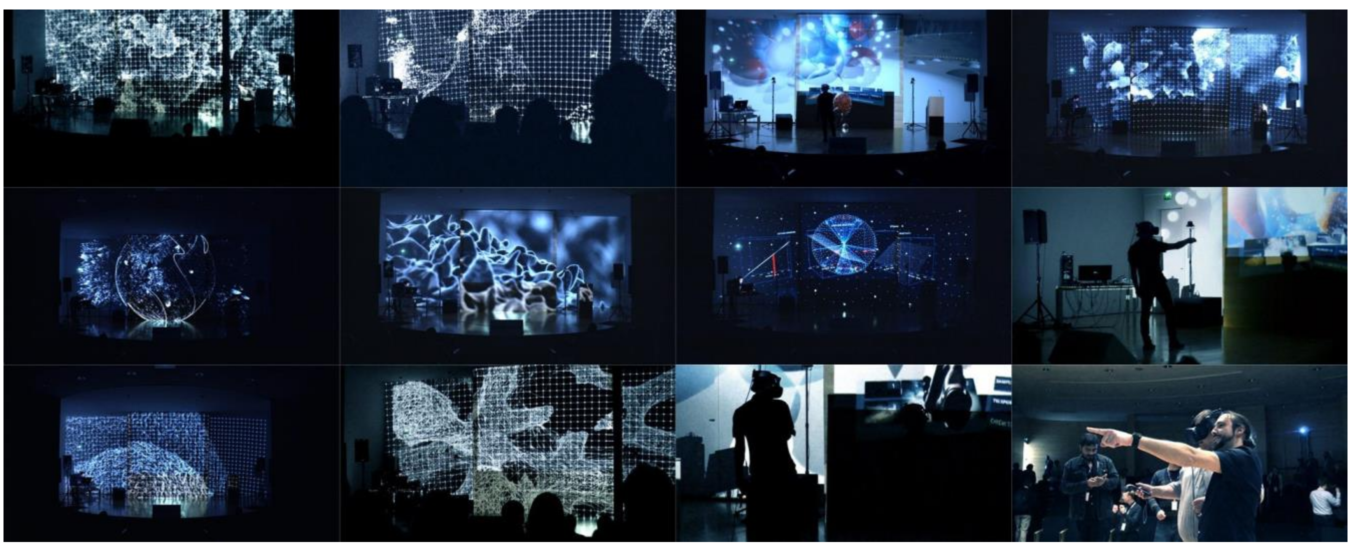


Figure 13: pictures of the performance at the INL main auditorium. In the last picture: the moment where researchers explored the virtual reality scenario.

This camera contained scripts that made quick head movements smoother by interpolating three-dimensional values acquired by the sensor into half-second time spaces. As the virtual camera was behind the artist, the movement of his hands, playing on the nanoclusters, could also be well perceived by the audience. The entire setup required several high-performance computers, because in addition to the image that was being rendered directly on the artist's helmet, several real-time images of the various virtual cameras, covering the entire performance, were also being rendered. Artist developed all performance's software, using open-source development kit OpenFrameworks [51], and also Unity3D [52] for the 3D simulations. Real-time virtual reality work on stage demands considerable efforts to happen, once there are many risks of failure, and previous work, with direct embodied technologies, in virtual reality, was successfully tested and presented to large audiences on stage [53]. The artist had a virtual interface, with virtual buttons, where he could change perspectives, and also freely move around the nano-space. Each virtual camera was rendering images for software that mapped all the stage space through NDI technology [54], with a few seconds of latency.

In this sense, it was a pioneering nano-scale live performance, at stage, in virtual reality, and the sensation of immersion was achieved by the audience, which was composed of senior researchers accustomed to high-performance scientific visualizations. The performance had the duration of 20 minutes, between audiovisual work (presented in the first 10 minutes), corresponding to first observations at the 1mm scale, and also audiovisual algorithms related to the first visualizations in the residency. In the middle of the performance, a moment in total immersion happened: the artist entered in an imagined energetic field, through an imagined capsule being sent to the nano-space.

He then loaded two types of nanoclusters generated by the SIN group in Aalto. The clusters slowly felt in the surface. With one hand controllers, he could launch molecules that were being attracted by the nanoclusters, and with the other hand controller, he could move in, approaching the 1nm scale. After the performance, the artist spoke with the scientists and invited them to experience nano-cluster virtual reality simulation. An unexpected gift to those researchers who dedicated their last years to this research (Fig 13).

7 Conclusions

This work represents a joint and multi-disciplinary effort that was achieved because of different visions came together. We conclude that it is challenging but very interesting having artists working in scientific research centers since they offer different visions, positive risks, other perspectives, which can complement the research in course. We reinforce the idea proposed by John Maeda, where he says that innovation happens when convergent thinkers combine forces with divergent thinkers, and art and science – once inextricably linked, both dedicated to finding truth and beauty – are better together than apart [55].
The technology and creativity developed in the course of this residence demonstrated interest and engagement by the researcher teams, and the new visual and interactive approaches inspired the CritCat research community, providing new visions and different scenarios of collaboration. It is also important to note that the artist, at the end of his residency, devoted some of his time transferring all the knowledge obtained to the different teams of scientists, including the source code and the methodologies he used in the creative process. The SIN group team acquired virtual reality equipment to take their research and visualization to new endeavors. Virtuality technologies are relevant when we want to access inaccessible spaces, especially in areas like nanotechnology, fostering new ways to explore undiscovered realities, expanding our imagination, and the need to know more. This result was achieved with inter-disciplinary work where attention to detail was the most distinctive feature in the process, via creative activity and visual thinking [56]. The introduction of a media artist in the team made possible new discussions related to the visualization of nanoclusters, since as the artist presented new prototypes, specifically in virtual reality, visual scenarios, although corresponding to simulations, gave rise to new thoughts and possibilities in the area of scientific representation. The EU STARTS program is an excellent opportunity of joining these ecosystems, and the results presented in this publication highlight what Gerfried Stocker, Director of Ars Electronica, mentioned in his recent discourse, at the Aalto Media Lab, in 2019, reinforcing the idea of the artist role in the human-machine encounter: 'still we're looking at products a lot from the point of view of the technology and less from the human perspective. A fluent synergy between art and technology or design and science might not only bring solutions but more – inspiration, impact, and new ideas' [33].

A first work-in-progress presentation was made at Centre Pompidou, Paris, in April 2019. In the same month, VR performance happened at INL, main auditorium. Starting in 15 of May, 'Sci-fi Miners' was presented to a wider audience, at the Art Center Nabi, in Seoul, Republic of Korea, not as performance, but in the form of multiple large façade displays, and a virtual reality experience for the general public, during three months, a solo exhibition by João Martinho Moura, named 'Confluence Point' [57] (Figs. 14-20).

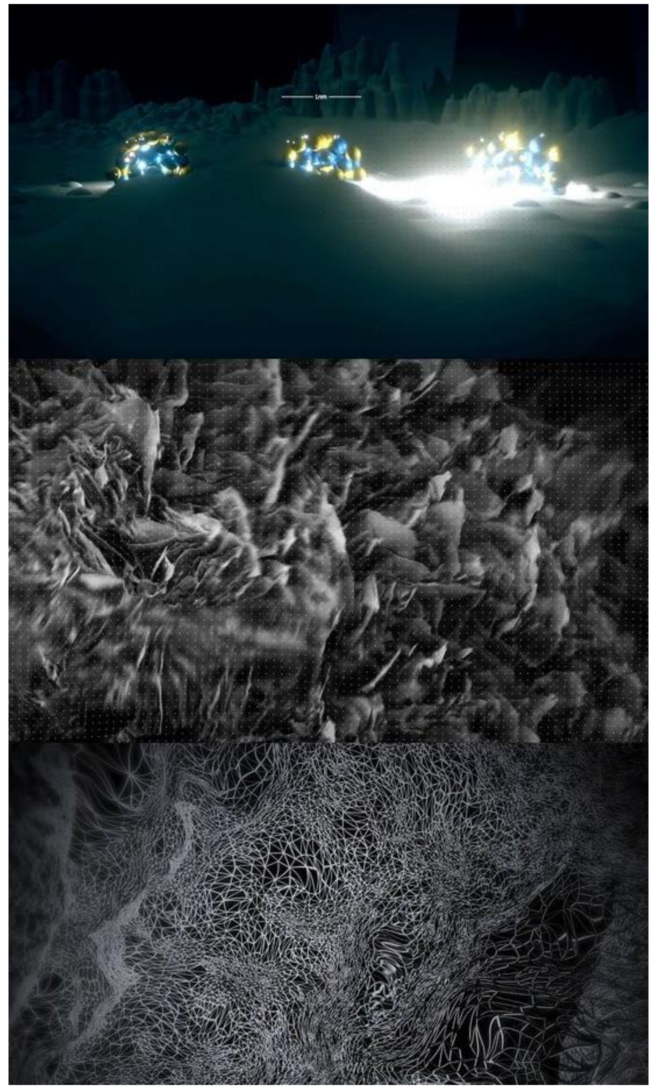
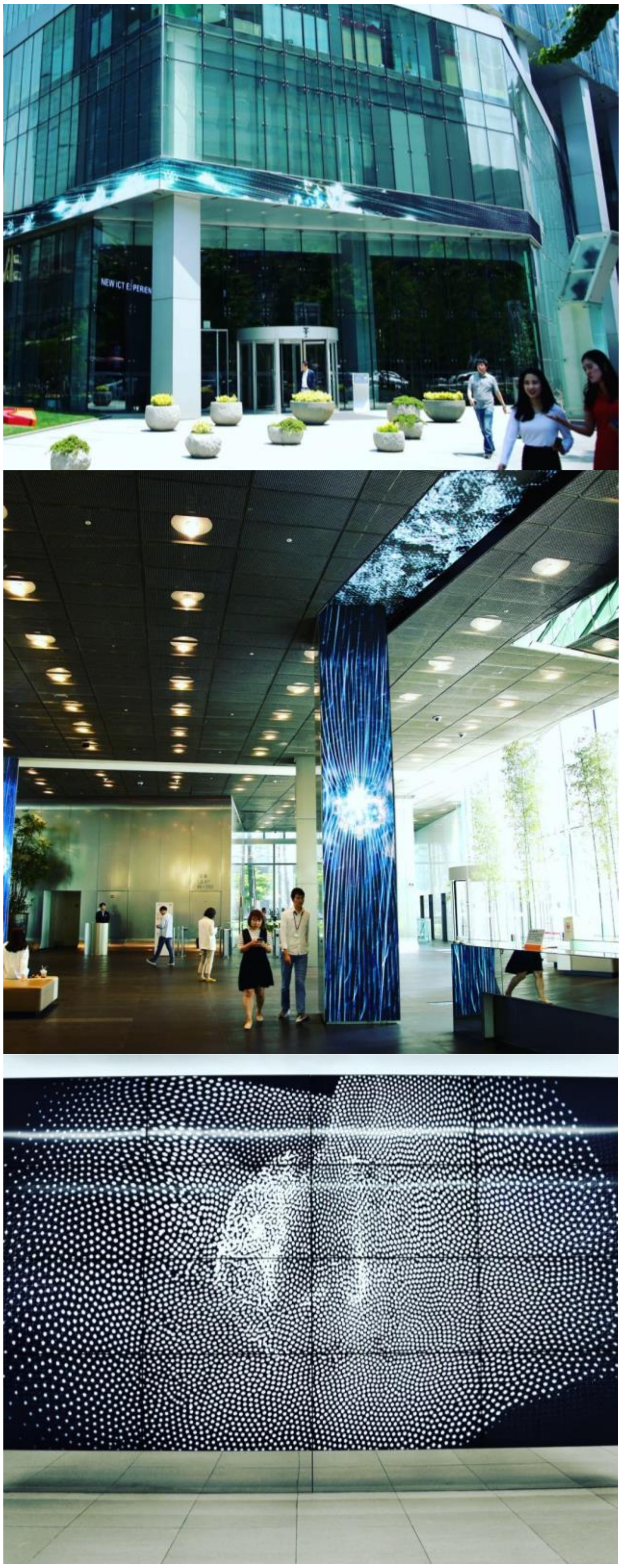


Figure 14-16: Sci-fi Miners. Audio-visual work: CritCat matter in different scales. b) Computed nanoclusters in VR (1nm); c) and d) visual abstractions from microscope observations, real and reconstructed imaginary.

Figure 17: a participant in Seoul, South Korea, at Art Center Nabi, experiencing 'Sci-Fi Miners' in Virtual Reality. 'Confluence Point', solo exhibition, by João Martinho Moura, 2019.



Figures 18,19,20: at Art Center Nabi, in Seoul, 'Sci-Fi Miners': audiovisual work presented in multiple façades a) exterior building; b) interior; c) wide screens. 'Confluence Point', solo exhibition, by João Martinho Moura, 2019.

Work designed by João Martinho Moura with the support of the STARTS Residencies as part of the STARTS program of the European Commission, based on the technological elements of the CritCat Project.

Video and images of the performance and exhibitions are available at: http://jmartinho.net/sci-fi-miners/

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REFERENCES

[1] A. K. Yetisen *et al.*, Mar-2016. Art on the Nanoscale and beyond, *Advanced Materials*, vol. 28, no. 9. Wiley-Blackwell, pp. 1724–1742, Mar-2016. DOI: 10.1002/adma.201502382 ISBN: 1521-4095 ISSN: 15214095.

[2]. STARTS - Innovation at the nexus of Science, Technology, and the ARTS. [Online]. Available: https://www.starts.eu/about-starts/. [Accessed: 02-Jul-2019].

[3]. Sci-Fi Miners | João Martinho Moura. [Online]. Available: http://jmartinho.net/sci-fi-miners/. [Accessed: 02-Jul-2019].

[4]. CritCat - João Martinho Moura | VERTIGO Starts Residencies. [Online]. Available: https://vertigo.starts.eu/calls/2017-2/residencies/sci-fi-miners/detail/. [Accessed: 20-Jun-2018].

[5]. CritCat - Rational design of future catalyst materials. [Online]. Available: http://www.critcat.eu/. [Accessed: 02-Jul-2019].

[6]. Partners - CritCat. [Online]. Available: http://www.critcat.eu/summary/partners. [Accessed: 02-Jul-2019].

[7] Deloitte Sustainability, Bureau de Recherches Géologiques et Minières, and N. O. for A. S. Research, 2017. *Study on the review of the list of critical raw materials - Publications Office of the EU*. 2017 ISBN: 978-92-79-47937-3.

[8] Rachel Nuwer, Mar-2014. What is the world's scarcest material?, Mar-2014. [Online]. Available: http://www.bbc.com/future/story/20140314-the-worlds-scarcest-material. [Accessed: 02-Jul-2019].

[9] J. L. Zell, 2006. Putting a Mine on the Moon: Creating an International Authority to Regulate Mining Rights in Outer Space, *MINN. J. INT'L L.*, vol. 15, p. 489.

[10] Leonard David, . Is Moon Mining Economically Feasible? | Space. [Online]. Available: https://www.space.com/28189-moon-mining-economic-feasibility.html. [Accessed: 02-Jul-2019].

[11] H.-W. Schutt, 1992. *Eilhard Mitscherlich: Prince of Prussian Chemistry*. Deutshes Museum, Merk & Co., Inc, 1992 ISBN: 0-8412-3345-4.

[12] Wikipedia, . Catalysis. [Online]. Available: https://en.wikipedia.org/wiki/Catalysis. [Accessed: 12-May-2019].

[13] J. Wisniak, Jan. 2010. The History of Catalysis. From the Beginning to Nobel Prizes, *Educación Química*, vol. 21, no. 1, pp. 60–69. DOI: 10.1016/S0187-893X(18)30074-0 ISSN: 0187-893X.

[14] R. P. Feynman, 1960. There's Plenty of Room at the Bottom, *Engineering and Science*, vol. 23, no. 5, pp. 22–36. DOI: 10.1201/9780429500459-7.

[15] The Royal Society and The Royal Academy of Engineering, 2004.

Nanoscience and nanotechnologies: opportunities and uncertainties, London, 2004. DOI: 10.1007/s00234-004-1255-6 ISBN: 0023400412556 ISSN: 0028-3940.
[16] N. Taniguchi, 1974. On the Basic Concept of Nanotechnology, in *Proceedings of the International Conference on Production Engineering*, 1974, pp. 18–23.
[17] C. Toumey, Apr. 2009. Truth and Beauty at the Nanoscale, *Leonardo*, vol. 42, no. 2, pp. 151–155. DOI: 10.1162/leon.2009.42.2.151 ISSN: 0024-094X.
[18] L. Mignonneau and C. Sommerer, 2005. Nano-Scape : Experiencing Aspects of Nanotechnology through a Magnetic Force-Feedback Interface, *Proceedings of the 2005 ACM SIGCHI International Conference on Advances in computer entertainment technology*, pp. 200–203. DOI: 10.1145/1178477.1178507 ISBN: 1-59593-110-4.
[19] V. Vesna and J. K. Gimzewski, 2005. NANO: An Exhibition of Scale and Senses, *Leonardo*, vol. 38, no. 4, pp. 310–311. DOI: 10.1162/0024094054762070 ISSN: 0024-094X.
[20] D. S. Goodsell, Aug. 2006. Seeing the nanoscale, *Nano Today*, vol. 1, no. 3, pp. 44–49. DOI: 10.1016/S1748-0132(06)70079-2 ISBN: 1748-3387 ISSN: 17480132.
[21] H. Hawkins and E. R. Straughan, Jan. 2014. Nano-art, dynamic matter and the sight/sound of touch, *Geoforum*, vol. 51, pp. 130–139. DOI: 10.1016/j.geoforum.2013.10.010 ISSN: 00167185.
[22] O. Grau and T. Veigl, 2013. Introduction: Imagery in the 21st Century, in *Imagery in the 21st Century*, MIT Press, 2013, pp. 1–16. DOI: 10.7551/mitpress/9780262015721.003.0001 ISBN: 0262015722.
[23] J. M. Moura, J. Llobet, M. Martins, and J. Gaspar, 2019. Creative Approaches on Interactive Visualization and Characterization at the Nanoscale, *Lecture Notes of the Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering, LNICST*, vol. 265, pp. 121–132. DOI: 10.1007/978-3-030-06134-0_13.
[24] L. P. L. Gonçalves *et al.*, May 2019. Combined experimental and theoretical study of acetylene semi-hydrogenation over Pd/Al2O3, *International Journal of Hydrogen Energy*. DOI: 10.1016/J.IJHYDENE.2019.04.086 ISSN: 0360-3199.
[25] I. Chakraborty and T. Pradeep, 28-Jun-2017. Atomically Precise Clusters of Noble Metals: Emerging Link between Atoms and Nanoparticles, *Chemical Reviews*, vol. 117, no. 12. pp. 8208–8271, 28-Jun-2017. DOI: 10.1021/acs.chemrev.6b00769 ISSN: 15206890.
[26]. Catalyst nanoparticles - CritCat. [Online]. Available: http://www.critcat.eu/concept/catalystnanoparticles. [Accessed: 03-Jul-2019].
[27]. Nanochemistry - Micro and Nanofabrication. INL. [Online]. Available: https://inl.int/micro-nanofabrication/nanochemistry/. [Accessed: 04-Jul-2019].
[28]. Surfaces and Interfaces at the Nanoscale (SIN) | Aalto University. [Online]. Available: https://www.aalto.fi/en/department-of-applied-physics/surfaces-and-interfaces-at-the-nanoscale-sin. [Accessed: 02-Jul-2019].
[29]. Rare metals - CritCat. [Online]. Available: http://www.critcat.eu/concept/raremetals. [Accessed: 03-Jul-2019].
[30] J. Watts, . Resource extraction responsible for half world's carbon emissions | Environment | The Guardian. [Online]. Available: https://www.theguardian.com/environment/2019/mar/12/resource-extraction-carbon-emissions-biodiversity-loss. [Accessed: 03-Jun-2019].
[31] D. M. Foster, T. Pavloudis, J. Kioseoglou, and R. E. Palmer, Dec. 2019. Atomic-resolution imaging of surface and core melting in individual size-selected Au nanoclusters on carbon, *Nature Communications*, vol. 10, no. 1, p. 2583. DOI: 10.1038/s41467-019-10713-z ISSN: 2041-1723.
[32] B. Fry and C. Reas, 2001. Processing.org, *Processing*, 2001. [Online]. Available: https://processing.org/.
[33]. Gerfried Stocker: Creativity requires nurture | Aalto University. [Online]. Available: https://www.aalto.fi/en/news/gerfried-stocker-creativity-requires-nurture. [Accessed: 04-Jul-2019].
[34] Apr. 2018. Krios TEM.
[35] R. G. Parr, 1980. Density Functional Theory of Atoms and Molecules, in *Horizons of Quantum Chemistry*, Dordrecht: Springer Netherlands, 1980, pp. 5–15. DOI: 10.1007/978-94-009-9027-2_2.
[36] L. H. Thomas, Jan. 1927. The calculation of atomic fields, *Mathematical Proceedings of the Cambridge Philosophical Society*, vol. 23, no. 5, pp. 542–548. DOI: 10.1017/S0305004100011683 ISSN: 0305-0041.
[37] R. Car and M. Parrinello, Nov. 1985. Unified Approach for Molecular Dynamics and Density-Functional Theory, *Physical Review Letters*, vol. 55, no. 22, pp. 2471–2474. DOI: 10.1103/PhysRevLett.55.2471 ISSN: 0031-9007.
[38] M. Lima, 2011. *Visual complexity : mapping patterns of information*. Princeton Architectural Press, 2011 ISBN: 978-1568989365.
[39] F. B. Viégas and M. Wattenberg, 2007. Artistic Data Visualization: Beyond Visual Analytics, *Online Communities and Social Computing*, vol. 4564, no. HCII 2007, LNCS 4564, pp. 182–191. DOI: 10.1007/978-3-540-73257-0_21 ISBN: 9783540732563 ISSN: 0302-9743.
[40] C. Johnson, Jul. 2004. Top scientific visualization research problems, *IEEE Computer Graphics and Applications*, vol. 24, no. 4, pp. 13–17. DOI: 10.1109/MCG.2004.20 ISBN: 0272-1716 VO - 24 ISSN: 02721716.
[41] C. M. Walker, E. Winner, L. Hetland, S. Simmons, and L. Goldsmith, Mar. 2011. Visual Thinking: Art Students Have an Advantage in Geometric Reasoning, *Creative Education*, vol. 02, no. 01, pp. 22–26. DOI: 10.4236/ce.2011.21004 ISSN: 2151-4755.
[42] W. R. Sherman and A. B. Craig, 2003. Understanding Virtual Reality—Interface, Application, and Design, *Presence: Teleoperators and Virtual Environments*, vol. 12, no. 4, pp. 441–442. DOI: 10.1162/105474603322391668 ISBN: 1558603530 ISSN: 1054-7460.
[43] American Society of Photogrammetry., C. C. Slama, C. Theurer, and S. W. Henriksen, 1980. *Manual of photogrammetry*. American Society of Photogrammetry, 1980 ISBN: 0937294012.
[44] L. Manovich, Mar. 2011. What is visualisation?, *Visual Studies*, vol. 26, no. 1, pp. 36–49. DOI: 10.1080/1472586X.2011.548488 ISBN: 1472-5878 ISSN: 1472586X.
[45]. Critical Raw Materials Reduction in Catalysis Workshop | Partial-pgms. [Online]. Available: http://www.partial-pgms.eu/critical-raw-materials-reduction-in-catalysis-workshop/. [Accessed: 04-Jul-2019].
[46] B. Bennett, 2001. Space, time, matter and things, in *Proceedings of the international conference on Formal Ontology in Information Systems - FOIS '01*, 2001, pp. 105–116. DOI: 10.1145/505168.505179 ISBN: 1581133774.
[47] Jan. 1961. Sensorama simulator.
[48] H. Rheingold, 1991. *Virtual reality*. Summit Books, 1991 ISBN: 0671693638.
[49] I. E. Sutherland, 1965. The ultimate display, *Proceedings of the Congress of the Internation Federation of Information Processing (IFIP)*, pp. 506–508.
[50] S. S. Fisher, Dec. 2016. The NASA ames VIEWlab Project-A brief history, *Presence: Teleoperators and Virtual Environments*, vol. 25, no. 4, pp. 339–348. DOI: 10.1162/PRES_a_00277 ISSN: 15313263.
[51] Z. Lieberman, A. Castro, and O. Community, 2004. Openframeworks, 2004. [Online]. Available: http://openframeworks.cc.
[52] Unity Technologies, . Unity. [Online]. Available: https://unity3d.com/pt. [Accessed: 21-Nov-2018].
[53] J. M. Moura, N. Barros, and P. Ferreira-Lopes, 2019. From real to virtual embodied performance-a case study between dance and technology (accepted), in *Proceedings of the 25th International Symposium on Electronic Art (ISEA 2019)*, 2019.
[54]. NewTek NDI. [Online]. Available: https://www.newtek.com/ndi/. [Accessed: 06-Jul-2019].
[55] J. Maeda, 2013. STEM + Art = STEAM, *The STEAM (Science, Technology, Engineering, Arts, and Mathematics) Journal*, vol. 1, no. 1, pp. 1–3. DOI: 10.5642/steam.201301.34 ISBN: 2327-2074 ISSN: 23272074.
[56] A. G. P. Brown, Nov. 2003. Visualization as a common design language: connecting art and science, *Automation in Construction*, vol. 12, no. 6, pp. 703–713. DOI: 10.1016/S0926-5805(03)00044-X ISSN: 0926-5805.
[57] J. M. Moura, 2019. Sci-Fi Miners - Art Center Nabi, "Confluence Point" exhibition. Seoul, South Korea | João Martinho Moura, 2019. [Online]. Available: http://jmartinho.net/sci-fi-miners/sci-fi-miners-art-center-nabi-confluence-point-exhibition-seoul-south-korea/. [Accessed: 03-Jul-2019].