Multi-scale Physicalization of Polar Heritage at Risk in the Western Canadian Arctic

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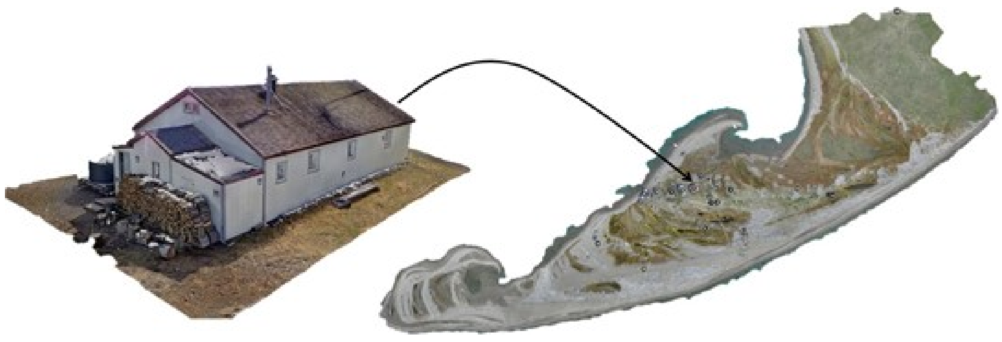

Fig. 1. Multi-scale presentation of the community house on the island.

Abstract—The digital preservation of heritage resources has emerged as an essential method for communicating the significance of artifacts, buildings, and landscapes to descendant communities and the wider public. While virtual representations are becoming more commonplace, physical representations (physicalization) of heritage sites via 3D printing are used to a lesser degree. Physicalization provides new perspectives through the interplay between touch and vision and can facilitate a deeper understanding of the history being conveyed. This paper discusses how the physical models of heritage buildings and landscape features on Qikiqtaruk/Herschel Island Territorial Park were created from terrestrial laser scanning and UAV photogrammetry data. We demonstrate how to use this physicalization of polar heritage to communicate the significance of the buildings and landscape of the island to the local Indigenous communities and global audiences, as well as how they are being threatened by climate change. We also explore the transformation of a cove on the island into puzzles and data sculptures. In addition to the Cove, the fabricating of important buildings on larger scales has been a requirement. This multi-scale printing raises the issue of connecting the large-scale buildings with their small instances/copies on the Island (similar to focus + context visualization in the digital form). Due to the limitation of physicalization compared with digital representations, new methods, metaphors and designs are needed for supporting focus + context visualization. We have designed and implemented several such methods in our specific physicalization of heritage buildings and landscape on Qikiqtaruk/Herschel Island. We presented our physicalizations to the members of the the Inuvialuit community of Aklavik NWT and received a positive response.

Index Terms—Physicalization, Heritage

1 INTRODUCTION

The visualization of heritage resources has become an important method for communicating the significance of artifacts, buildings, and landscapes to descendant communities and the wider public. Qikiqtaruk/Herschel Island Territorial Park is an important heritage site in the Western Canadian Arctic. Qikiqtaruk and its heritage resources are currently being threatened by storm surges and erosion caused by sea ice depletion due to the ongoing impacts of climate change [37].

In general, historical sites are commonly preserved using digital archaeology through non-intrusive photogrammetry techniques such as aerial photography and high-accuracy 3d scanning [33]. With the help of 3D graphics and vision-based reconstruction methods the resulting imagery and point clouds are converted to 3D models [3]. Furthermore, semi-automatic interactive image-based methods are used for fine-tuning and augmenting digital content [38].

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Specific to this work, terrestrial laser scanning and drone-based photogrammetry were used to digitally capture historic resources at risk of loss. These include historic buildings from the whaling and fur trade eras and Indigenous Inuvialuit sod houses dating from the precontact to historic period [7]. The resulting digital imagery (point clouds) accurately captures the detailed geometry and colour of all the buildings, their locations, and the landscape of the site. The digital imagery from Qikiqtaruk is currently stored in an online archive, along with historical background information and photographs of each heritage feature [7]. Drone imagery of the Cove also reveals how the shoreline has dramatically changed over time and how this change currently threatens a majority of Qikiqtaruk's historic resources [22].

This extensive and important digital dataset, which includes a high-quality, detailed digital model of Pauline Cove and its buildings, provides an excellent opportunity for employing creative visualizations and novel methods to communicate the stories about this heritage site. Several advanced visualization methods and digital tools (e.g., VR tools) can be used to present this type of data. However, high technical digital tools such as gaming computers, high-speed internet connections, and the necessary technical support are not always accessible to Aklavik, Tuktoyuktuk, and Inuvik – three Inuvialuit communities with close cultural connections to the heritage resources of Qikiqtaruk/Herschel Island. Outside of remote northern regions, the recent movement to online social interaction for work and school has illustrated that a digital divide exists, albeit nowhere near as pronounced [9–13, 29–31].

Physicalization (i.e. visualizing data using physical models) provides a tangible experience in a self-exploratory and engaging manner [16,46]. For example, scale models of important landmarks have been historically used in many sites [7, 20, 24]. However, it is challenging to create accurate scale models of complex objects with details using traditional tools. Making a replication of the scaled model or modifying components of the model is another challenge. Recently 3D printers have been used to simplify the construction method and better respect the input data. However, 3D printing has its limitations (e.g., limited size platform, low rendering speed). Rendering a well-designed physicalization requires creative methods and an iterative approach to take the high quality and complex data sets, such as Pauline Cove, and generate printable segments, optimize the printing process, and assemble the fabricated pieces into tangible models. Another critical challenge in physical models is to support multi-scale representation. Although, the problem of physicalization for geospatial data and regions have been explored in other works [1, 16, 17], the support for multi-scale still remains a big challenge. In digital form, models can be trivially scaled up or down using a combination of simple tools such as scaling transformation and camera setup and more advanced techniques such as level-of-details [39]. However, supporting similar tools in physical forms such as globes is a a non-trivial challenge [27]. Furthermore, there exist advanced visualization techniques such as focus + context visualization, which help to keep track of context while exploring the focus concurrently [23, 36, 42].

In this paper, we introduce a novel multi-scale physicalization used for heritage sites and historical buildings using affordable 3D printers. We consider Pauline Cove as the case study and access its high resolution point cloud from the Qikiqtaruk/Herschel Island Digital Heritage Archive [7]. We also introduce three new methods for Focus+ context Physicalization. The size and scale of the physical model is critical; large physical models are challenging to move, and printing them takes up more time and materials. Smaller models, on the other hand, can't present enough details of the site.

In the first step we convert this point cloud into a water-tight 3D mesh that can be used in 3D printers. The resulting mesh is usually noisy, high resolution and may contain non-manifold segments with inconsistent normals. Therefore, at the pre-processing stage, we denoise, clean, repair and simplify the mesh. Also, the scanning can create some undesired 3D objects (e.g., gas containers or water tank shown in the Figure 1) which are not part of the historical site. We use interactive modelling software to remove these undesired features.

There exist several types of 3D printers with many variations. We use FDM printers [18], because they are affordable, portable and lightweight. Therefore, it is easy to use them in-site supports (e.g., repeating the fabrication of the model), as well as running workshops and events for visitors and educational purposes. However, FDM printers are slow, have small printer beds and support only a limited number of colours. Therefore, it is necessary to employ a careful design and fabrication process to compensate these limitations. Also, to better visualize the historical buildings, we explore the idea of removable roof (similar to exploded view introduced in [19]). Further, to support engaging and tangible activities related to the physical model, we designed jigsaw puzzle for the entire Cove. The size limitation of the 3D printer forced us to segment the entire mesh into smaller pieces. This segmentation can be done automatically using non-linear optimization methods [1]. Alternatively, iterative mesh editing tools can be used when full control of the segmentation is required. Since the physical model is decomposed into many printed segments, a method for connecting the pieces is needed (e.g., pin/hole). Finally, the scale of the physical model should be carefully chosen. A large-scale model would be hard to move (particularly to remote communities) and place on tables. Furthermore, the fabrication of the large model would become slow and expensive. On the other hand, important features of the heritage sites may be lost in small-scale models. For example, the community house is an important landmark of Pauline Cove. Determining a single scale such that the community house is detailed enough (e.g., the scale of 30cm) leads to the need to build the entire Cove (see Figure 1) with a size of at least 3 meters. To address this issue, we explore the idea of multi-scale physicalization. In this method, the community house (or any other object of interest) is fabricated on a larger scale, while the entire Cove is printed on a smaller scale. Therefore, the objects of interest appear in two scales (see Figure 1). Consequently, a clear clue for connecting two instances is needed. Hence, we introduce multiple methods for the purpose of connecting these instances.

Fig. 2. Left:Takkakaw Falls. Right: Coronado Cove

Our main contribution is the design and fabrication of multi-scale physicalization for the heritage sites in Pauline Cove. Our design and models support Focus + Context visualization in physical forms.

2 Related Works

2.1 Visualization of Heritage Resources

Ioannides and Ewald in [24], justify the need for affordable 3D digitization technologies in the field of Cultural Heritage and explained its challenges. Heritage agencies such as Parks Canada rely primarily on visitor experience to relate key historic messages to the public [9]. However, the relative inaccessibility of polar heritage sites like Qikiqtaruk/Herschel Island due to their remote geographic location makes it challenging to communicate their significance to local and global audiences [9, 29]. There are even Inuvialuit living in communities such as Aklavik, Tuktoyaktuk, and Inuvik who are rarely able to visit Qikiqtaruk, even though it features prominently in their culture and history.

Dawson and colleagues have successfully used terrestrial laser scanning to digitally capture historic sites in the Canadian Arctic, such as Fort Conger Ellesmere Island and the Mackenzie Delta [4, 8, 9, 14, 15].

Techniques developed during these projects for using laser scanners in remote arctic regions were used to digitally capture historic resources on Qikiqtaruk/Herschel Island using Z + F 5010X and Leica BLK360 terrestrial laser scanners. A Sensefly Ebee Classic UAV with SODA camera was also deployed to capture Pauline Cove, where the majority of historic resources on the island are located. We started from this dataset for our approach to physicalization.

Virtual reality and physicalization are two promising approaches that allow visitors to explore the island and its heritage resources without the need to physically visit the site. On the virtual side, Dawson et.al [7] have created a digital heritage archive that provides users with opportunities to interact with 3D point clouds and meshes of every heritage building, as well as a bird's eye view of the island in the form of a photogrammetric 3D model of Pauline Cove [7] Physical models of these heritage resources can supplement their virtual counterparts or even serve as a substitute when access to internet connectivity and/or adequate computer hardware are limited.

2.2 Physicalization

Looking at museums and tourist information centers, it is common to find maquettes of heritage places, representing scaled models of attractive areas with some selective details. These physical models engage and draw the visitor's attention and are also very useful at conveying information of the specific places and their geographical and spatial relationships [34]. For example, when hiking on the Takakkaw Falls trail in the Rocky Mountains in Canada, a glass box displays a physical model of the terrain at the beginning of the trail. This physical model provides an overview of the trail and its relevant distance from the fall (See Figure 2 Left). As another example, there is an interesting

Fig. 3. Physical model of Quebec build by Jean- Baptiste Duberger between 1806 and 1808.

scale model in the vicinity of the lighthouse located in Coronado Island in California (See Figure 2 Right).

Figure2 shows a scale model of Quebec City built between 1806 and 1808 by draftsman Jean- Baptiste Duberger and British Royal Engineer John By exemplifies a type of graphic representation widely used by military engineers between the late 17th century and the mid-19th century [21]. This model was completed at a time when major military works were under construction in Quebec City. It was most likely intended for British military authorities, considering that it was sent to London in 1810

These examples and many other physical models used for communicating information to people show that physicalization can make the exploration of complex data-sets easier [16, 25]. Taher et. al. in [46] believed that physical visualizations are not only easy to handle and control, but they also improve human cognition through natural interaction. Furthermore, in [26], the authors justify the efficiency of information retrieval while using physical visualization in comparison with on-screen visualization by citing the memorability of physical models [45].

Recent improvements in digital fabrication have created more opportunities for physical visualization or physicalization. Today we see physicalization in various fields of science and art, areas like architecture, information visualization and scientific visualization [16]. For instance, architects use scale models for different purposes: from the exploration of the form to the presentation or display of architectural details and correlations [44]. In the scientific visualization, Ang et. al. designed a novel, slice-based physicalization method for better visualization of 4D nature of blood flow within the left ventricle [2].

In geography and science education, visualization and scaled models are crucial, especially when the context is too big to be presented in the classroom [27]. Classroom physical models (e.g., volcano example) are at the scale of centimetres while the analogous portion of the Earth System is at the kilometres. Physical visualization of Geospatial Data sets is a new area in visualization that supports the tactile exploration of geospatial data in different scales. In [16] authors use a Discrete Global Grid System (DGGS) to design such models, at different resolutions and scales, on which geospatial data sets can be attached. To justify the educational value of this physicalization, authors in [34] took the physical model into geography classrooms and observed the applicability of it from both student's side and teacher's side. Landscaper [1] took another step to fabricate a scaled model of Lauterbrunnen village in Switzerland as a popular tourist attraction, from the high-quality data of the place to detailed information of terrain and valley and rivers. They developed a system for creating these physical models using an affordable 3D printer to make their creation more widely accessible.

With all advancements in physical representations of data, the interaction with physicalization is still to further research [16]. Adding interaction to physicalization increases the tactile value of the model and provides more flexibility for exploration [43, 48]. Umetani and Schmidt in [47] try to post-assemble conductive tapes and foils on the surface of the 3D printed model with switches and lights for interaction. Further in Capricate [40] and Printput [6] authors include circuits in the process of prototyping using a conductive material.

Fig. 4. Herschel Island is located in the Beaufort Sea off the north coast of the Yukon Territory

2.3 The History of Qikiqtaruk/Herschel Island Territorial Park

Herschel Island is approximately 101 square kilometers in size, and is located in the Beaufort Sea off the north coast of the Yukon Territory (Figure 4). It was named after the English astronomer Sir William Herschel by John Franklin in 1826. American whaling ships used the island as a winter station in early 1889. It was during this time that Commander Charles H. Stockton of the USS Thetis named the island's geographical features. By 1883, reports of abuse by whalers towards Inuvialuit eventually led to the establishment of a Northwest Mounted Police Detachment on the island in 1903. Police presence remained on Herschel even after the whaling industry ended in 1914. By 1964, the island had no permanent population [35]

Pauline Cove is located on the northern corner of Qikiqtaruk/ Herschel Island Territorial Park Pauline Cove (see Figure 4), and is home to Inuvialuit and Euro-North American heritage resources that are currently threatened by storms, flooding, landslides and erosion caused by the disappearance of sea ice [5, 22, 28, 37]. Nineteen historic structures remain standing at Pauline Cove and are related to the American Steam Whaling Era and later fur trade in the late 19th and early 20th centuries. Alongside these are buildings associated with Anglican missionaries, the Northwest Mounted Police, the Hudson Bay Company and other traders. The Pacific Steam Whaling Company community house, which was built in 1893, is one of the most prominent structures on the island. It is the oldest framed building in the Yukon [5, 22].

Of equal significance are the remains of Inuvialuit settlements which are also present at Pauline Cove. The earliest evidence for Qikiqtariungmiut (or inhabitants of Qikiqtariuk) are from an archaeological site known as "Washout". The site, which once consisted of half a dozen semi-subterranean sod and driftwood houses, was occupied between 1200 AD and 1600 AD [5]. Since its discovery in 1954 by R.S. MacNiesh, erosion caused by storm surges has removed all trace of its existence. The inhabitants of Washout were the ancestors of all living Inuvialuit and Inuit in Canada [5]. Along with other archaeological sites on Qikiqtaruk/Herschel Island, these heritage resources document the accelerated pace of social change within Inuvialuit culture as whalers and other newcomers arrived in the Western Arctic.

In order to preserve and archive the heritage resources present at Pauline Cove, Dawson and colleagues, used a Sensefly Ebee Classic fixed-wing drone to digitally capture Pauline Cove on Qikiqtaruk/Herschel Island during July 2019. Using a ground sampling distance of 2.96cm, the resulting images covered an area approximately 18 hectares in size and were processed using Pix4D mapper. This resulted in a highly detailed point cloud and mesh of the terrain, including the coastline and historic buildings. Terrestrial laser scanning was used to capture each historic building at Pauline Cove digitally.

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Fig. 5. The digital model provided with scanners and drones captured all details including some that are not related to the historical background.

Building exteriors were captured using a Z+F 5010X laser scanner. A Leica BLK360 scanner was used to capture the interiors of all buildings, as well as the exteriors of a few of the smaller structures. This included the famous ice houses – subterranean structures constructed by Euro-American whalers to store whale blubber and other foods. These datasets are accessible at the University of Calgary's website dedicated to the digitally preserving Pauline Cove [7].

3 Design and Fabrication of the Basic Physicalization

In this section, we discuss the design and fabrication of the basic physicalization of Pauline Cove. Multi-scale physicalization of the Cove will be discussed in the next section.

3.1 Data

The process from data collection to the final fabricated physical model has several steps that are shown in Figure 6. Data collection is the first step. We were able to access and download the high resolution point cloud of the Pauline Cove from the Qikiqtaruk/Herschel Island Digital Heritage Archive which makes its content freely available under the Attribution-Non-Commercial Creatives Common License CC BY-NC 4.0 university of Calgary website [7]. The point cloud data is large and contains finer details about the Cove's dataset (i.e. terrain and shoreline), as well as all historical landmarks. The Cove dataset contain more than one million triangles and 500k vertices, and the dataset of the historical buildings has higher resolution. For example, the dataset for the community house contains 1.1 million triangles and 937k vertices.

3.2 Mesh processing and Fabrication

As shown in Figure 6, to fabricate the physical model of the Cove, we use the point cloud datasets and transform them into 3D meshes through multiple operations. In the first step, we use off the shelf software for converting point-cloud to a 3d mesh. The resulting mesh contains holes, non-manifold faces, and faces with inconsistent normals. These issues cause problems for creating proper printable objects (i.e. solid models), therefore, we edit the mesh using interactive modeling tools (e.g., MAYA) to create water-tight mesh for solid modeling. The scanner also usually captures some unwanted objects in the scene (e.g., the jacket or propane and water tanks in Figure 5). We use solid modeling tools to remove these unwanted objects and repair the missing pieces. Software packages such as 3D builder can also be used as they support some basic solid modeling operations. After these editing steps, we obtain a clean, water-tight 3D model of the Cove. Because 3D printers have a platform with a limited size, the resulting mesh is usually segmented into smaller pieces. These segmented mesh pieces are sent to the 3D printer for fabrication.

For fabricating the historical buildings (i.e. the community house and the bone house), we use the same process shown in Figure 6. The data captured for the interior of the buildings is cluttered by furniture and personal belongings of the residents (see Figure 7, Left). Consequently, many walls were covered fully or partially in the data. Also, the quality

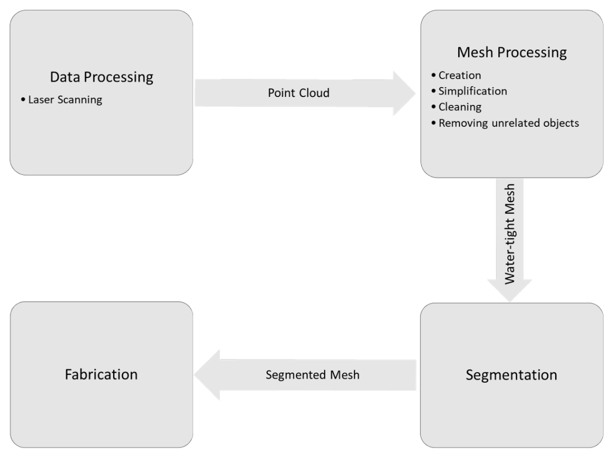

Fig. 6. The flowchart presenting the process from data to final physical model.

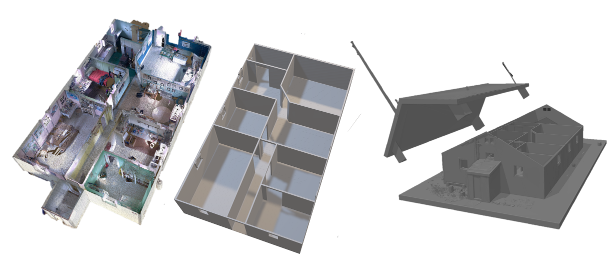

Fig. 7. Left: the interior point clouds. Middle: the result of interactive modelling. Right: the removable roof.

of collected ceiling data was poor as it contained many tears and holes. To address these issues, we used the point cloud primarily as a guiding reference to interactively model the interior walls and the ceiling (see Figure 7). Finally, we designed a removable roof for the houses to make the interior visible. To do this, we segmented the roof part from the rest of the house. Also, to make the roof steady, we added some pins underneath the top and some holes on the corners of the house (see Figure 7, Right.)

The left image in Figure 8 shows the digital model of the Cove after cleaning and editing. To render the physical model of the entire Cove we must decide on the scale of the model, as larger scales would be more challenging to handle, and smaller scales can't show enough details. To determine the scale, we must consider the two conflicting objective. The first is that, the historical buildings must be visible and identifiable. Being able to explore the spatial relationships between buildings, as well as between each building and the shoreline are helpful for communicating the geographical and spatial relationships. Also, this ability is valuable for conveying the significant impact of coastal erosion on the site, and the risk this poses to many of the heritage buildings. The second objective is that the physical model should be portable in order to be used in classrooms and cultural centers such as the one in the Yukon and Northwest Territories. To satisfy both of these objectives, we aimed for a desktop size (at most 120cm length) for the basic model of the Cove. This constraint is satisfied using a scale of 1 to 10000 for the entire Cove resulting a fabricated model with the size of $116cm \times 45cm$. However, such a size is not directly printable by most of the current 3D printers especially affordable printers such as our MakeGear M2 with the bed size of $20cm \times 23cm$. As a result, the model must be segmented to smaller pieces that are to be printed individually. The segmentation must be done such that to avoid cutting through important features (e.g., historical landmarks). For complex landscapes with many features, optimization technique used in [1] can be employed. For the Cove model, we managed to find simple cuts for decomposing the model to eleven pieces without cutting through the houses that are on it (See Figure 8 Right). Since the resulting pieces must be assembled and glued together, a set of connectors (e.g., pin/holes) can be added to the 3D models of each piece (see Figure 8 Right).

3.3 Double-Model Physicalization

The physical model of the Cove represents its overall landscape and geospatial information about the historical buildings, but it lacks specific details for each building. The community house in particular has important historical value and its point cloud contains extra details of both the exterior and interior of the house. However, these details are not visible in the scale 1 to 100000. In order to make more detailed physicalization of this building, we constructed a separate but larger model of the house. This is similar to the method used in the traditional physical scaled models in tourist attraction areas. For example, Figure 9 shows two models from the light house in Coronado Island. One of a larger map of the area, and another of a smaller portion of the same map that has more details in that it contains notable landmarks, such as the famous lighthouse of the island.

Additionally, to visualize the details of the interior plan of the building, we designed a removable roof. Because of this, we constrained the scale to be small enough so visitors can grab it with both hands and explore it in more direct ways, to see the inside. On the other hand, it should be large enough to show certain details of the building like the windows and interior walls. Consequently, we built a 1 to 50 ($30cm \times 45cm$) scale of the Community House as a separate model to accompany the Cove physical model (See Figure 10).

Considering our 3D printers bed sizes, we had to segment the building into pieces (six pieces, four base and two roof) that were printable. Figure 11 shows the community house and the Cove in both digital and physical form. The scale of the house is 1 to 50 and the scale of the Cove is 1 to 100000.

3.4 Texture and Color

The final 3D printed models contained many little details, however not every detail is clearly visible due to the model being printed all white. We considered several options for addressing this issue. One possible option is to print an atlas of texture images and attach them to the physical model using adhesive material [32, 41]. The other option is to manually paint the physical model with realistic color considering the photos of the real building. Figure 12, the left image shows the paper print of the textures atlas of the house for covering the physical model. The right image shows the house that half of the model is covered with the printed papers. The left image in the Figure 11 shows the community house after being painted and added some textured grass by an artist.

3.5 Puzzle

The ability to create physical models opens a door to many novel ways for visualizing data. Tangibility is one of the main advantages that physicalization brings [16, 25]. This motivated us to design a jigsaw puzzle model of the Cove to support playfulness and encourage curiosity by putting the puzzle pieces representing the different parts of the Cove together. As the first step we decide on the type of the puzzle, number of pieces and the size of the final physical model (i.e. the scale).

Starting with a simple jigsaw puzzle 2D pattern, we built 3D digital puzzle pieces using 3D extrusion of the 2D pieces (see Figure 13). Then we find the solid intersection between these 3D puzzle pieces and the 3D model of the Cove. During the intersection process, we must avoid cutting through important features like buildings, or leaving small remaining pieces (see Figure13). When creating the mesh models of the puzzle pieces it is important to leave small gaps by offsetting the boundary curves to allow assembling and disassembling to be simple and easy. Further,

4 Focus + Context Physicalization

As we discussed in section 3, multiple scales of the landmarks can be fabricated and use to physicalize the Cove and its important places. However, as evidenced in the Figure 11 the relationship between the large scale of Community house and its smaller size on the Cove is not clear. In fact, the focus (Community house) is not well connected to the context (the Cove). The challenge is how we can keep the context while exploring the focus in the physical form and connect it to the context. The challenge is more complex when there are more than one focused object in the context (See Figure 14). As evidenced in the literature there are several creative tools and methods to support this concept in the digital world. For example authors designed highlighters in [42] to support several points of focus while maintaining the surrounding context (See Figure 16).

4.1 Designing Focus + Context Physicalization

The Cove physicalization is a good example to justify the need for a well-designed connections between the context and the focus in physical form. There are more than fifteen important historical buildings and landmarks on the Cove, and it is difficult to recognize the association between larger and smaller models of the same subject on the Cove.

To overcome this challenge, we came up with three different design solutions to properly showcase the focus + contest in the physicalized setup.

4.1.1 Color Association

The first of these solutions is to use distinguishable colors to make connection between different scales of structures by color association. Figure 15 shows our attempt to build this approach of multi-scale physicalization of the Cove with two of its historically important buildings. This design is simple to understand and completely tactile. Based on color variety in 3D printing, we can build as many distinguishable focus points on the Cove.

To execute this design, when we printed the larger models of the Community House and Bone House, we had their roofs printed in different colors (green for the Community House and red for the Bone

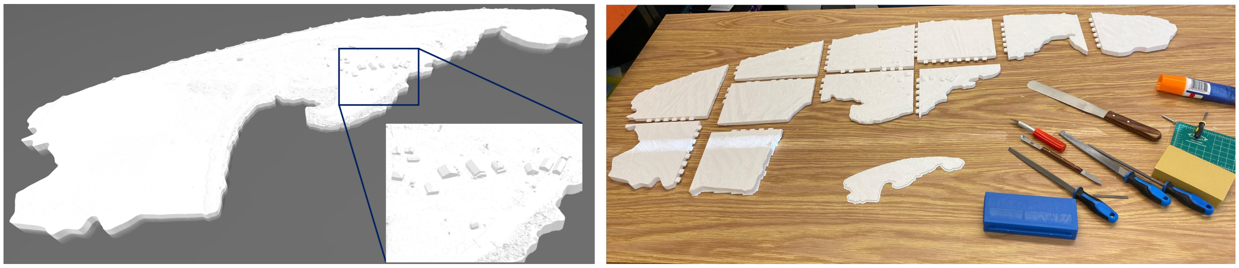

Fig. 8. Left: digital model of the Cove. Right: The Cove was segmented into pieces that fit the 3D printer.

Fig. 9. Physical display of Coronado Island and its famous light house in California.

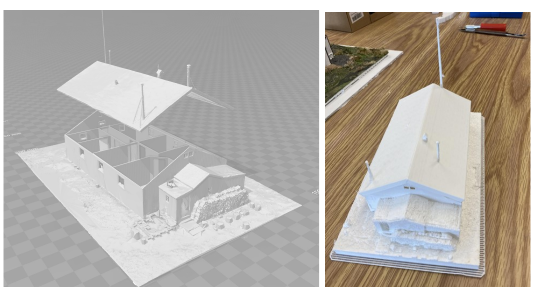

Fig. 10. The Community House in the scale of 1 to 50. Left: digital. Right: physical.

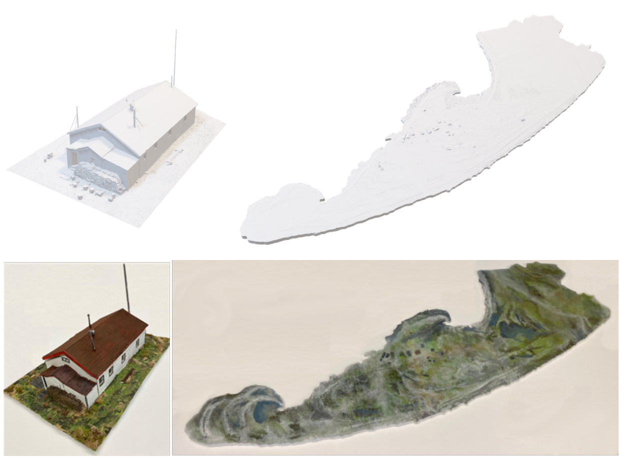

Fig. 11. Left: the community house in the scale of 1 to 50. Right: Pauline Cove in the scale of 1 to 100000 digital model on top and painted physical model on bottom.

Fig. 12. Exploring the idea of texture atlas for covering the physical model.

House). Then when printing the full model of the Cove, for the roofs of the smaller versions of those buildings, we gave them the same colors as the buildings they are meant to represent. In this approach, we need to use mono-colour for all parts of physical model except to focal.

4.1.2 Connectors

In our second solution, we utilize physical highlighters to support the connector concept in focus + context in physicalization. This is inspired by the highlighters used in the digital world model (as demonstrated in Figure 16), only the highlighters in this instance are tangible to signify where the larger model of the building is in physical model of the Cove. This is demonstrated in Figure 17 left, where the larger model of the specific building being focused on is physically connected to its location on the Cove.

To implement this design in a physical space we constructed an elevation platform to place the larger models of the buildings on, placing it above the model of the Cove near their smaller versions. We then placed a transparent colored paper shaped as a triangle between the two models of the buildings and the Cove (See Figure 17 Right).

This mimics the look of a highlighter in a digital setup when zooming into something (such as with Figure 16) and communicates that the two models are of the same subject, just presented at different scales. We preserve the distance between the smaller versions of the buildings on the Cove model and the larger version of the buildings. This design is also relatively simple to produce but both of these physicalizations are passive [17].

4.1.3 Touch via Active Physicalization

In our third design we utilize active physicalization [17] and support simple touch interactions. This can not only support the concept of focus + context but will open new doors for adding narratives and other storytelling ideas into the physical world. Our desired design is to have a setup that supports touch interaction. For example, when the visitor touches the large scale of the house, the corresponding landmark on the Cove lights up (e.g., using LED), and if the landmark on the Cove is touched, the larger scale of the house is highlighted the same way (See Figure 18).

To execute this design, we considered two different setups for different modes of touch interactions. In one, shown in the Figure 19, touching the smaller house model on the Cove causes the larger model of the same building to light up. This is due to a connected circuit box

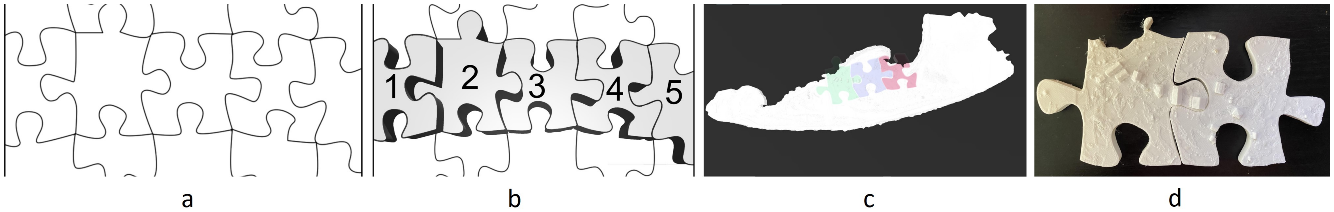

Fig. 13. Puzzle design for the Cove. a: 2D jigsaw puzzle layout, b: 3D extrusion, c: solid intersection, d: the final puzzle pieces.

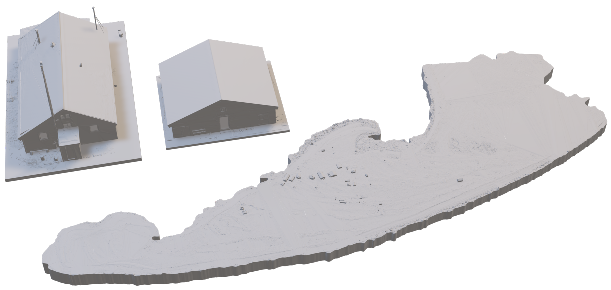

Fig. 14. Digital models of bone house and community house in the scale of 1 to 50. Pauline Cove in the scale of 1 to 100000.

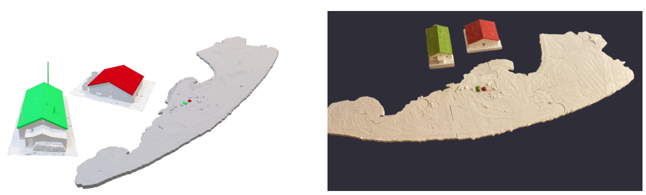

Fig. 15. Left: digital, Right: physical model of bone house and community house and the Cove using colors to make connection

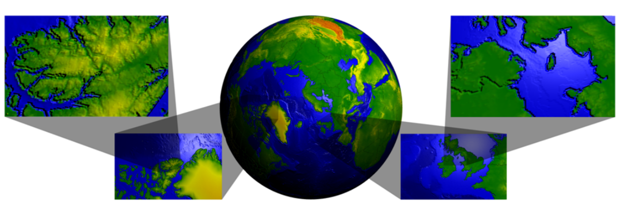

Fig. 16. The concept of Focus + Context in digital visualization. The highlighter is used to connect the focus to the context.

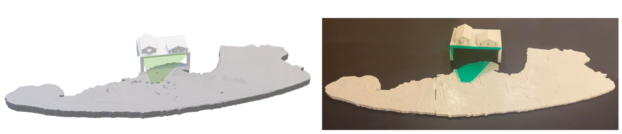

Fig. 17. Left: the design of physical highlighter. Right: using highlighter in physicalization.

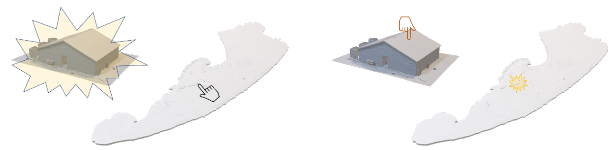

Fig. 18. Two sided interaction with the physical model. Left: the landmark on the Cove lighted when the larger scale of the house is touched. Right: the large scale of the house is lighted when the corresponding landmark on the Cove is touched.

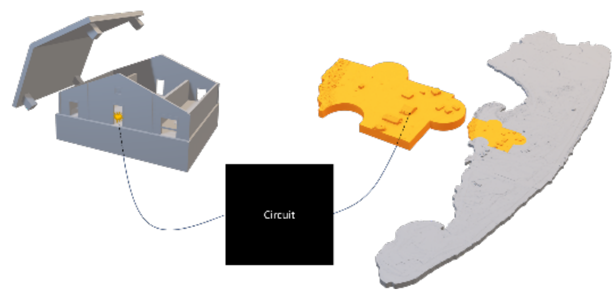

Fig. 19. Schematic representation of the touch design for the physicalization.

(shown in the Figure 20, in both digital and physical form) with an attached LED.

The box is mounted underneath the larger house model with the LED poking out through a hole we made in the floor. We use conductive filament to form the open circuit, the two ends of which are on each side of the smaller house model on the Cove. This circuit will then be closed by someone touching the model, as shown in Figure 21, causing the LED to light up.

In the second set up, as shown in Figure22, touching the roof of the larger model of the house (specifically the two letters engraved into the roof) causes the smaller model of the same building on the Cove to light up. This is due to (as shown in Figure 20), an open LED circuit placed

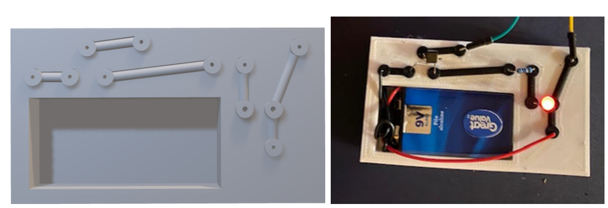

Fig. 20. The design of the circuit box is in a way that can hold the battery and be embed underneath the house model.

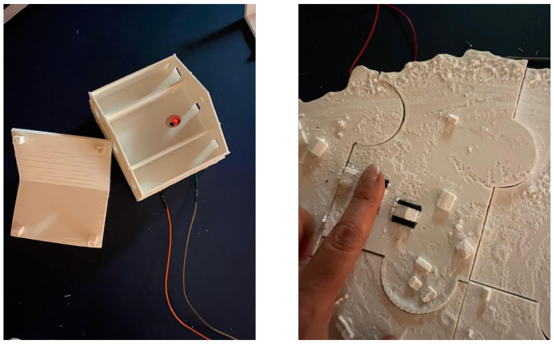

Fig. 21. Interaction with physicalization using conductive filaments and LED, design-1.

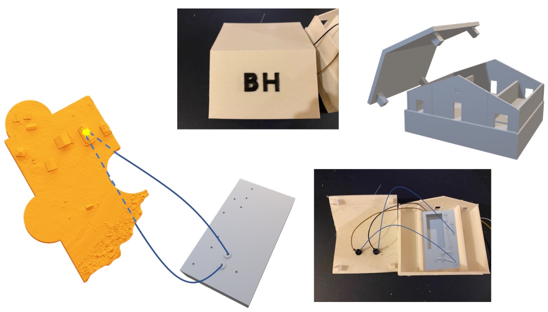

Fig. 22. Schematic representation of the touch design for the physicalization.

directly under the smaller house model, which in this set up is made with transparent material to better conduct the light. The two ends of the open circuit are connected to the two letters that are engraved into the roof of the house, which are made of conductive material. In this instance, the circuit is closed by a person touching the two letters causing the LED to light up.

4.1.4 Comparison

The colour association provides a simple solution to the problem of Focus + Context Physicalization. The main limitation of this method is when the final physicalization must be painted or printed with the color and textures (see Fig 11, Bottom). The connector solution can address this issue, but it requires more time in manual assembly. Both color association and connector solutions will be less practical when having many foci. On the other hand, active physicalization can address these challenges with the cost of using a dedicated circuit. Compared with the colour association and the connector methods, the active physicalization requires a more complex fabrication and access to a battery or power plugs.

5 Results

During the month of January 2020, members of our research group, travelled to the Inuvialuit community of Aklavik to present the physicalizations of Qikiqtaruk/Herschel Island to members of the Aklavik Hunters and Trappers Committee, as well as community leaders. The response was overwhelmingly positive, with those in attendance remarking that being able to touch and hold buildings and landscape features created a sense of place (See Figure 24). The models also provided an opportunity for community members to recall events and stories, suggesting that physicalizations of heritage may function as mnemonic devices. Finally, members of the Hunters and Trappers Committee saw great potential for the 3D physicalizations as ways to teach young Inuvialuit about the history and landscape of Qikiqtaruk. The geographic remoteness and relative inaccessibility of polar heritage sites such as Qikiqtaruk Herschel Island Territorial Park makes it difficult to communicate key messages of heritage significance to the general public. This is highly problematic as polar heritage sites are some of the most at-risk heritage because of the relentless impacts of climate change in polar regions of the world. Digitally capturing historic buildings and cultural landscapes in these regions is one potential solution, but limited internet connectivity and a lack of up-to-date computer hardware in many northern communities makes it difficult to engage northern communities with virtual heritage exhibits. Physicalizations via 3D printed models offer a promising alternative.

6 Conclusion

Like many polar heritage sites, Qikiqtaruk/Herschel Island is being heavily impacted by climate change effects and human caused destruction. The historic buildings and archaeological sites constitute a cultural landscape that traces the development of Inuvialuit culture as well as the dramatic changes brought about by the arrival of whalers, traders, missionaries and police. Communicating the key messages associated with arctic climate change and the island's complex Cultural and natural history is challenging because of its remote geographical location. Poor internet connectivity and a lack of access to computer hardware can further complicate matters – especially when communicating virtual content to northern communities affected by the digital divide. Physicalizations side step such issues by offering a means of representing cultural landscapes in three dimensions, and in ways that can be touched and manipulated by users. Climate change data, along with the stories and lived experiences of the island's inhabitants can then be mapped onto the physicalization in the form of colors, touch designs, and interactive puzzle-making.

Our observations of Inuvialuit interacting with the physicalizations of Pauline Cove and the Pacific Stream Whaling Company Community House suggest that the ability to touch, hold, and manipulate these models allows users to accurately recall both the cultural and natural landscape of the island. For example, all attendees regularly visit Qikiqtaruk/Herschel Island to hunt, fish, and gather with family members, and have done so since they were children. Heritage buildings and other cultural and natural features represented on the physical model of Pauline Cove were instantly recognized by excited attendees as they ran their fingers over its surface. The more the models were handled, the more stories about the island were shared. Likewise, interacting with the Community House model prompted several Inuvialuit to comment on other historic buildings they have observed on the Yukon North Slope that are also eroding into the Beaufort Sea. This prompted a discussion about climate change and the need to protect heritage sites at risk in the region. Physical models of other digitally captured heritage sites should similarly impact users, especially those with close connections to the resource.

Future research will explore how these physicalizations can be used to support classroom lesson plans aimed at teaching Indigenous and Settler students about Qikiqtaruk and polar heritage at risk.

There are several directions in which this work can be extended. Dedicated user studies can be designed and performed to support and evaluate the effectiveness of different physicalizations in education and tourism applications. Also, creating interactive physicalization that connects elements of the physical model to the associated information in digital archives will be another natural direction for future work. Adding time-varying data (e.g. flood risk map, shoreline change) into the physicalization will also create an excellent opportunity for educating the next generation.

References

[1] K. Allahverdi, H. Djavaherpour, A. Mahdavi-Amiri, and F. Samavati. Landscaper: A modeling system for 3d printing scale models of landscapes. In *Computer Graphics Forum*, vol. 37, pp. 439–451. Wiley Online Library, 2018.

[2] K. D. Ang, F. F. Samavati, S. Sabokrohiyeh, J. Garcia, and M. S. Elbaz. Physicalizing cardiac blood flow data via 3d printing. *Computers & Graphics*, 85:42–54, 2019.

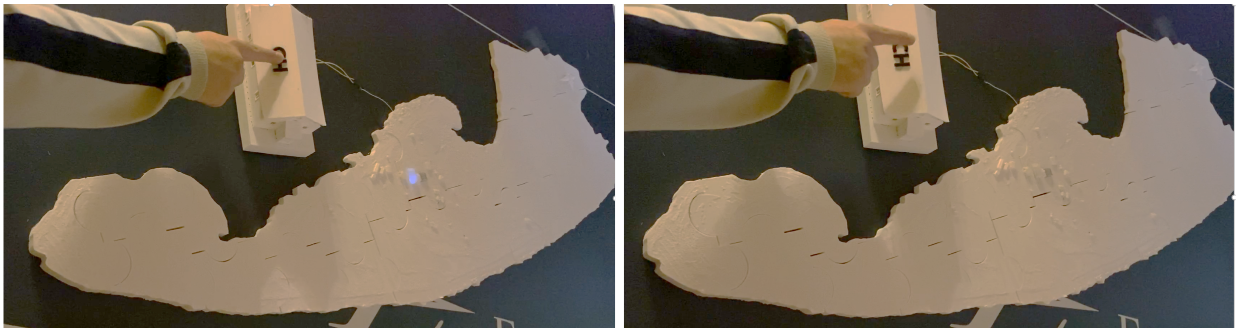

Fig. 23. Interaction with physicalization using conductive filaments and LED, design-2.

Fig. 24. Manny Arey from Aklavik holds a 3D printed model of the community house from Qikiqtaruk.

[3] M. Berger, A. Tagliasacchi, L. M. Seversky, P. Alliez, G. Guennebaud, J. A. Levine, A. Sharf, and C. T. Silva. A survey of surface reconstruction from point clouds. In *Computer Graphics Forum*, vol. 36, pp. 301–329. Wiley Online Library, 2017.

[4] M. M. Bertulli, L. Dick, P. C. Dawson, and P. L. Cousins. Fort conger: A site of Arctic history in the 21st century. *Arctic*, pp. 312–328, 2013.

[5] C. R. Burn. Herschel Island qikiqtaryuk: a natural and cultural history of Yukon's Arctic Island. *Calgary, Alberta*, 2012.

[6] J. Burstyn, N. Fellion, P. Strohmeier, and R. Vertegaal. Printput: Resistive and capacitive input widgets for interactive 3d prints. In *IFIP Conference on Human-Computer Interaction*, pp. 332–339. Springer, 2015.

[7] P. Dawson. Digitally preserving Herschel Island-Qikiqtaruk Territorial Park, Yukon Territory. `https://herschel.preserve.ucalgary.ca/`.

[8] P. Dawson, M. Bertulli, L. Dick, and P. L. Cousins. Heritage overlooked and under threat: Fort conger and the heroic age of polar exploration. In *Identity and Heritage*, pp. 107–115. Springer, 2015.

[9] P. Dawson and R. Levy. From science to survival: Using virtual exhibits to communicate the significance of polar heritage sites in the Canadian Arctic. *Open Archaeology*, 2(1), 2016.

[10] P. Dawson, R. Levy, D. Gardner, and M. Walls. Simulating the behaviour of light inside Arctic dwellings: implications for assessing the role of vision in task performance. *World Archaeology*, 39(1):17–35, 2007.

[11] P. Dawson, R. Levy, and N. Lyons. Breaking the fourth wall: 3d virtual worlds as tools for knowledge repatriation in archaeology. *Journal of Social Archaeology*, 11(3):387–402, 2011.

[12] P. Dawson and R. M. Levy. Using 3d computer models of inuit architecture as visualization tools in archaeological interpretation: two case studies from the Canadian Arctic. In *Dynamics of Northern Societies, SILA/NABO Conference on Arctic and North Atlantic Archaeology, Copenhagen*, pp. 10–14, 2004.

[13] P. Dawson and R. M. Levy. Constructing a 3d computer model of a thule whalebone house using laser scanning technology. *Journal of Field Archaeology*, 30:443–55, 2005.

[14] P. Dawson, R. M. Levy, G. Oetelaar, C. Arnold, D. Lacroix, and G. Mackay. Documenting mackenzie inuit architecture using 3d laser scanning. *Alaska Journal of Anthropology*, 7(2):29–44, 2009.

[15] P. C. Dawson, M. M. Bertulli, R. Levy, C. Tucker, L. Dick, and P. L. Cousins. Application of 3d laser scanning to the preservation of fort conger, a historic polar research base on northern ellesmere Island, Arctic Canada. *Arctic*, pp. 147–158, 2013.

[16] H. Djavaherpour, A. Mahdavi-Amiri, and F. F. Samavati. Physical visualization of geospatial datasets. *IEEE computer graphics and applications*, 37(3):61–69, 2017.

[17] H. Djavaherpour, F. Samavati, A. Mahdavi-Amiri, F. Yazdanbakhsh, S. Huron, R. Levy, Y. Jansen, and L. Oehlberg. Data to physicalization: A survey of the physical rendering process. *Computer Graphics Forum*, abs/2102.11175, 2021. doi: 10.1111/cgf.14330

[18] P. Dudek. Fdm 3d printing technology in manufacturing composite elements. *Archives of metallurgy and materials*, 58(4):1415–1418, 2013.

[19] A. Florio, M. Trapp, and J. Döllner. Semantic-driven visualization techniques for interactive exploration of 3d indoor models. In *2019 23rd International Conference Information Visualisation (IV)*, pp. 25–30. IEEE, 2019.

[20] E. Georgiou, E. Karachaliou, and E. Stylianidis. 3d representation of the 19th century balkan architecture using scaled museum-maquette and photogrammetry methods. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 42, 2017.

[21] C. Government. Fortifications of quebec national historic site. 2017. [Online; accessed 19-July-2021].

[22] Y. Government. Herschel Island: Qikiqtaruk a guide to historic resources. c. s. b.-h. s. 2013.

[23] M. Hasan, F. F. Samavati, and C. Jacob. Interactive multilevel focus+ context visualization framework. *The Visual Computer*, 32(3):323–334, 2016.

[24] M. Ioannides and Q. Ewald. 3d research challenges in cultural heritage. *Lecture notes in computer science*, 8355:151, 2014.

[25] Y. Jansen and P. Dragicevic. An interaction model for visualizations beyond the desktop. *IEEE Transactions on Visualization and Computer Graphics*, 19(12):2396–2405, 2013.

[26] Y. Jansen, P. Dragicevic, and J.-D. Fekete. Evaluating the efficiency of physical visualizations. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pp. 2593–2602, 2013.

[27] K. A. Kastens and A. Rivet. Using analogical mapping to assess the affordances of scale models used in earth and environmental science education. In *International Conference on Spatial Cognition*, pp. 112–124. Springer, 2010.

[28] H. Lantuit, W. Pollard, N. Couture, M. Fritz, L. Schirrmeister, H. Meyer, and H.-W. Hubberten. Modern and late holocene retrogressive thaw slump activity on the Yukon coastal plain and Herschel Island, Yukon Territory, Canada. *Permafrost and Periglacial Processes*, 23(1):39–51, 2012.

[29] R. Levy and P. Dawson. From laser scanning to virtual reality: The art and science of constructing a thule whalebone house. In *EdMedia+ Innovate Learning*, pp. 4537–4541. Association for the Advancement of Computing in Education (AACE), 2005.

[30] R. Levy and P. Dawson. Interactive worlds as educational tools for understanding Arctic life. *Past Play: Teaching and Learning History with Technology*, pp. 66–86, 2014.

[31] R. M. Levy and P. Dawson. Exploring Arctic cultures: Constructing a virtual world for the geode, a 3d virtual reality theatre.

[32] A. Mahdavi-Amiri, P. Whittingham, and F. Samavati. Cover-it: an interactive system for covering 3d prints. In *Proceedings of the 41st Graphics Interface Conference*, pp. 73–80, 2015.

[33] J. McCarthy. Multi-image photogrammetry as a practical tool for cultural heritage survey and community engagement. *Journal of Archaeological Science*, 43:175–185, 2014. doi: 10.1016/j.jas.2014.01.010

[34] L. Moorman, H. Djavaherpour, K. Etemad, and F. F. Samavati. Geospatial physicalization in geography education. *Journal of Geography*, 0(0):1–13, 2020. doi: 10.1080/00221341.2020.1832138

[35] W. R. Morrison. Herschel Island. *In The Canadian Encyclopedia. Historica Canada.*, 2006. [Online; accessed 19-July-2021].

[36] J. F. Packer, M. Hasan, and F. F. Samavati. Illustrative multilevel focus+context visualization along snaking paths. *The Visual Computer*, pp. 1–16, 2016. doi: 10.1007/s00371-016-1217-0

[37] B. Radosavljevic, H. Lantuit, W. Pollard, P. Overduin, N. Couture, T. Sachs, V. Helm, and M. Fritz. Erosion and flooding—threats to coastal infrastructure in the Arctic: a case study from Herschel Island, Yukon Territory, Canada. *Estuaries and Coasts*, 39(4):900–915, 2016.

[38] F. Samavati and A. Runions. Interactive 3d content modeling for digital earth. *The Visual Computer*, 32(10):1293–1309, 2016. doi: 10.1007/s00371-016-1227-y

[39] B. Schmid, J. Schindelin, A. Cardona, M. Longair, and M. Heisenberg. A high-level 3d visualization api for java and imagej. *BMC bioinformatics*, 11(1):1–7, 2010.

[40] M. Schmitz, M. Khalilbeigi, M. Balwierz, R. Lissermann, M. Mühlhäuser, and J. Steimle. Capricate: A fabrication pipeline to design and 3d print capacitive touch sensors for interactive objects. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*, pp. 253–258, 2015.

[41] C. Schüller, D. Panozzo, A. Grundhöfer, H. Zimmer, E. Sorkine, and O. Sorkine-Hornung. Computational thermoforming. *ACM Transactions on Graphics (TOG)*, 35(4):1–9, 2016.

[42] M. Sherlock, M. Hasan, and F. Samavati. Interactive data styling and multifocal visualization for a view-aware digital earth. Technical report, Science, 2016.

[43] R. Slyper and J. Hodgins. Prototyping robot appearance, movement, and interactions using flexible 3d printing and air pressure sensors. In *2012 IEEE RO-MAN: The 21st IEEE International Symposium on Robot and Human Interactive Communication*, pp. 6–11. IEEE, 2012.

[44] M. Stavri, P. Sianin, and B. Tepavcevic. The use of scale models in architecture. In *Architectural Scale Models in the Digital Age*, pp. 41–83. Springer, 2013.

[45] S. Stusak, J. Schwarz, and A. Butz. Evaluating the memorability of physical visualizations. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, pp. 3247–3250, 2015.

[46] F. Taher, J. Hardy, A. Karnik, C. Weichel, Y. Jansen, K. Hornbæk, and J. Alexander. Exploring interactions with physically dynamic bar charts. In *Proceedings of the 33rd annual acm conference on human factors in computing systems*, pp. 3237–3246, 2015.

[47] N. Umetani and R. Schmidt. Surfcuit: Surface-mounted circuits on 3d prints. *IEEE computer graphics and applications*, 37(3):52–60, 2017.

[48] K. Willis, E. Brockmeyer, S. Hudson, and I. Poupyrev. Printed optics: 3d printing of embedded optical elements for interactive devices. In *Proceedings of the 25th annual ACM symposium on User interface software and technology*, pp. 589–598, 2012.