ECE 445

SENIOR DESIGN LABORATORY

DESIGN DOCUMENT

AR Sandbox

Team #3

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Contents

1 Introduction

1.1 Problem Statement

We are introducing a smart sandbox with augmented reality (AR) capabilities that projects contour maps in real-time onto the sand surface, making geography education for children not only informative but also significantly more enjoyable. Currently available educational sandboxes [1] [2] are mostly cumbersome and limited to public spaces like activity centers rather than serving as personalized learning tools. Ffor AR sandbox which are able to project contours onto the sandbox, problems emerges. A high lagging time can be noticed when sand is manipulated manually causing contours being recalculated and re-projected onto the terrain. Meanwhile, contours are flickering on the terrain parts that remain still for the whole time, showing heavy amount of computational resources are wasted on the unnecessary parts thus restricting more delicate and faster signal processing procedure on the terrain parts that need to be updated as soon as possible. Furthermore, the existing projectors designed for sandboxes exhibit primitive features, characterized by a notably low refresh rate and harsh direct light that arise safety concerns for children's eyesight.

We introduce a smart sandbox with AR capabilities that projects contour maps in real-time onto the sand surface, making geography education for children not only informative but also significantly more enjoyable. We are committed to addressing these drawbacks and are working towards the development of a new and improved AR sandbox. This innovative solution aims to overcome the limitations of bulkiness, offering a more accessible and personal learning experience. Additionally, we are focused on enhancing the AR functionality to deliver a smoother experience with higher refresh rates and reduced glare, ensuring a more comfortable and engaging educational tool for children.

1.2 Solution Overview

We would develop a next-generation sandbox with AR projection and interaction capabilities. Basic criterions for our sandbox are: safe, easy to use and high refresh rate. The overall structure will be designed to be portable while ensuring both high load-bearing capacity and stability. The AR module, including depth camera, processing unit and projector, can be removed from the sandbox and installed on other sand tables. In general, our project will ensure a refresh rate of 30 fps, and the contours can be accessed wirelessly from portable mobile devices. The projector can be auto focused to ensure display clarity when projector's installation is changed to another sand table or the height of sandbox is altered. The depth camera will be used to detect the height of the sand and collect RGB and IR image for excluding human hands from the height change. The projector will be high luminance to display clearly on sand and short throw to match the camera's field of view and lower the center of mass for safety. The AR module will interact with people through the projected screen or mobile devices.

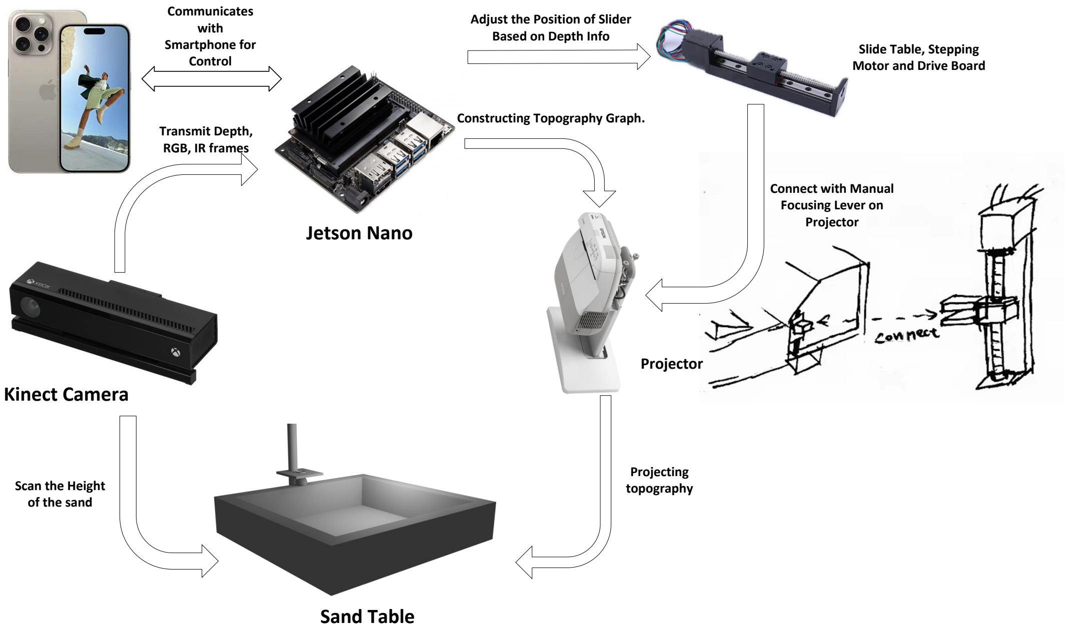


Figure 1: Visual Aid for AR Sandbox Project

1.3 High-Level Requirements

- The AR module must have a refresh rate of projected topography of at least 30 fps and low latency.
- The AR module must be able to correctly exclude human hands from the height change of sand.
- The AR module must be easy to use, pushing one button to start and interact with people only through the projected screen.
- The sandbox must be portable and foldable for easy transportation and storage.
- The AR module must be able to adapt to different kinds of sand and sand table.

2 Design

2.1 Subsystem Overview

The AR sandbox project consists of five subsystems: sensor, processing, projection, powering, and structure. The sensor subsystem is responsible for acquiring depth information from the sand surface. The processing subsystem is responsible for processing the depth information and projecting the correct topography graph onto the sand. The display subsystem is responsible for projecting the topography map onto the sand surface. The powering subsystem is responsible for providing power to the sensor, processing, and display subsystems. The structure subsystem is responsible for storing the sand and connecting to all the other parts as a whole AR module. The block diagram for the AR sandbox project is shown in Figure 2.

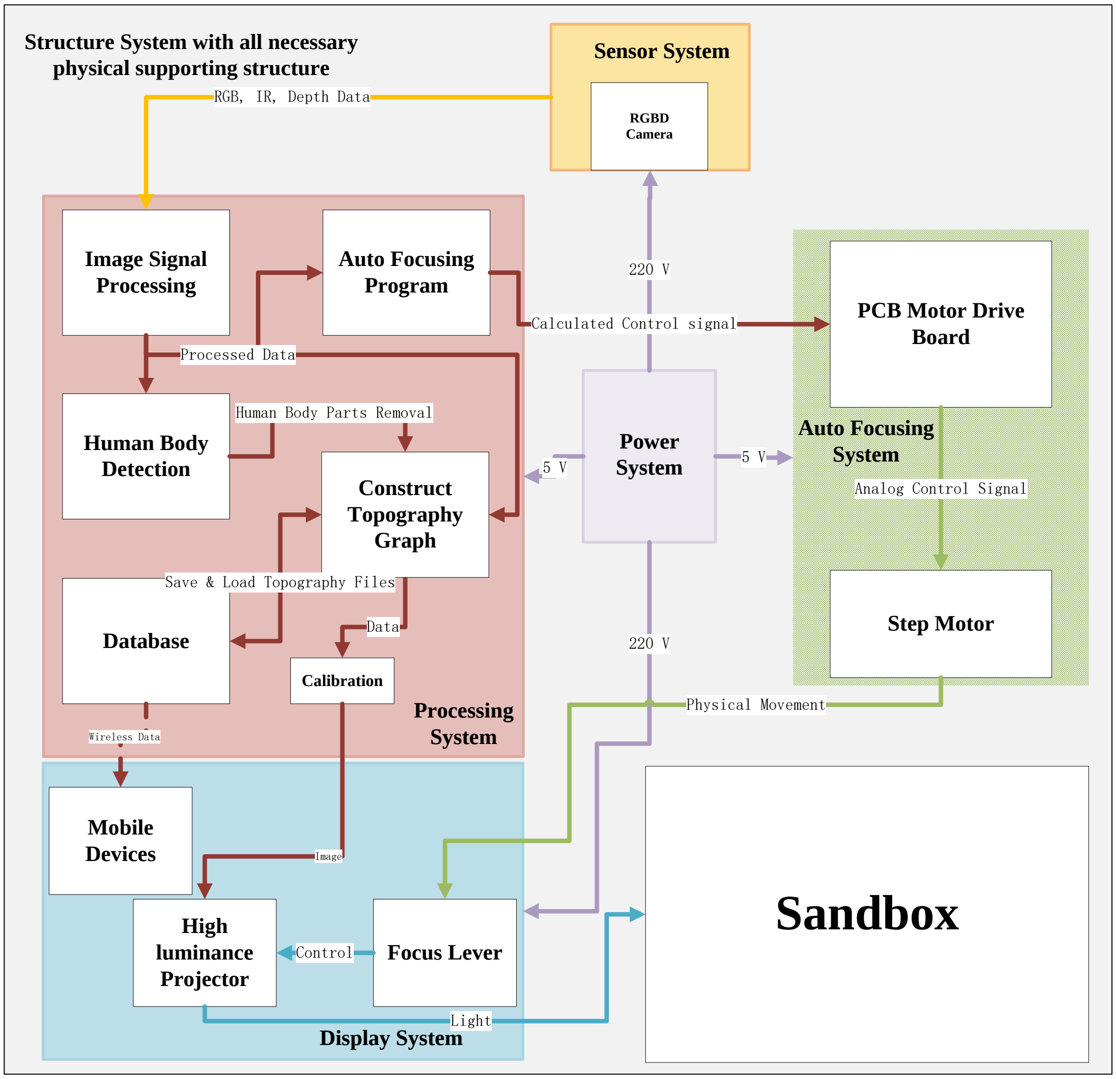


Figure 2: Block Diagram for AR Sandbox Project

2.1.1 Physical Design

The overall physical design of the sandbox is shown in Figure 3. The sandbox is primarily composed of two components: the body of the sandbox and detachable part performing AR functionality. The AR module, including the depth camera, processing unit, and projector, can be removed from the body of sandbox and installed on other tables.

The actual size of the sandbox and the detachable module is shown in Figure 5 and 6. The sensor would be placed right above the sandbox by a grippable bar, whose length can be adjusted from $46\,\mathrm{cm}$ to $74\,\mathrm{cm}$ as illustrated in Figure 4. The height of sensor from the sandtable would be $65\,\mathrm{cm}$ to ensure that its field of view matches the projected screen. The projector is $367 \times 143 \times 375\,\mathrm{mm}$.It would be embedded in the top $160 \times 380 \times 10\,\mathrm{mm}$ groove. The stepping motor would be installed on a linear sliding table with $50\,\mathrm{mm}$ stroke. They have the size of $28 \times 34 \times 125\,\mathrm{mm}$. The sliding table connects with the focusing lever on the projector.

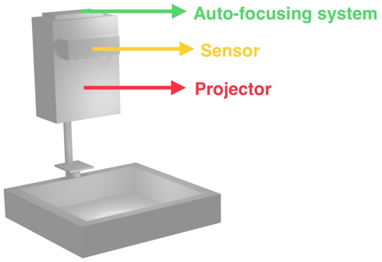


Figure 3: Overall Physical Design of the Sandbox

Figure 4: Grippable Bar for the Sensor and Projector Installation

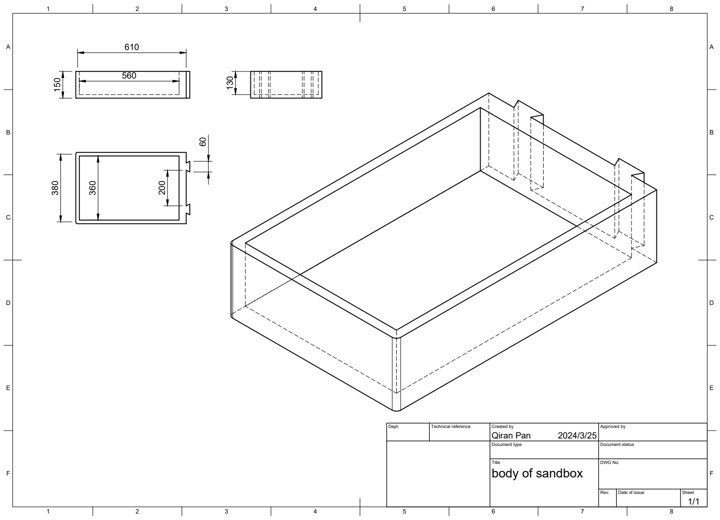


Figure 5: Design of the Sandbox's Body

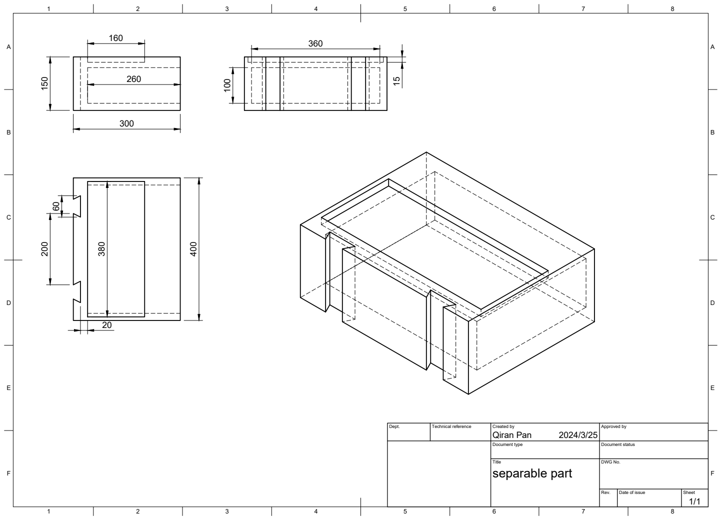


Figure 6: Design of the Sandbox’s Removable Part

2.1.2 Sensor Subsystem

The sensor subsystem is responsible for acquiring depth information from the sand surface. To project the correct topography graph onto the sand, the sensor subsystem must be able to provide depth information with high resolution and low latency and color data to segment human hands from the sand. This unit is crucial for the accuracy and speed of the topography rendering.

Figure 7: Microsoft Kinect V2 Camera

For this, we choose to use a Microsoft Kinect V2 camera as the depth sensor for our project. It has several advantages: it is capable of providing depth information in low light levels, providing RGB and IR frames and is color and texture invariant[3]. It has a color sensor with a 1920×1080 pixels resolution and a depth sensor with a 512×424 pixels resolution. The operational area is delineated by a depth span from 0.5 to 4.5 meters, with a viewing angle of $70°$ horizontally and $60°$ vertically [4]. The sensor communicates with the processing unit through USB protocol. We use an open library called "libfreenect2" [5] to access the depth information from the Kinect V2 camera.

Requirement	**Verification**
The RGB, IR and depth frames should transmit to the processing unit at a frame rate of at least $30\,\mathrm{fps}$.	Run a program with basic frames retrieving and displaying function. Log the frame rate to verify if it reaches desired value.
The depth sensor should provide depth information with a resolution of 512×424 pixels.	Check the dimension readings of depth data in the code. It should be 512×424
The depth sensor should run for a long time without overheating or performance issues.	Run the sensor for at least one hour and log the frame rate. Check if the frame rate keeps above our desired value $30\,\mathrm{fps}$.

Table 1: Sensor Subsystem RV Table

2.1.3 Processing Subsystem

With the use of GPU acceleration on the Jetson platform, it sends the correct topography graph to the display subsystem based on height information from sensor subsystem. Here are a list of requirements for the processing subsystem:

- Human body detection is necessary to overcome the interference from human hands and head. With this to enable multi-user collaboration. The projector should be capable of accurately projecting contour maps onto the sandbox with more than 1 people playing with sand.
- Real-time topography rendering is for constructing topography map from depth information with GPU acceleration. The refresh rate should be higher than $30\,\mathrm{fps}$. To verify the correctness of the projected contour maps, we will artificially create distinctive landforms such as ridges, valleys, and saddles, and compare them with the projected contour maps to ensure accurate alignment.
- Save and load topography functionality aims to build an interactive website that enables users to take a snapshot of a sand model and restore it at a later time. The website can be hosted directly on the Jetson Nano, and users can access the website on the same network via a specific hostname and port.

Body Detection To overcome interference from the human body, such as hands, arms, or heads, a body detection module is necessary. This module works as the flowchart showing below. It first resizes the RGB image from Kinect v2 and feeds it as input to the segmentation model. Then, the model detects human body parts and outputs an image with a per-pixel classification mask overlay. By doing this, we can ignore human body interference by keeping the original depth information for pixels that are part of the human body.

We plan to utilize Semantic Segmentation with the SegNet model [6] provided by Jetson Inference. Semantic segmentation is based on image recognition, except the classifications occur at the pixel level as opposed to the entire image. This is accomplished by convolutionalizing a pre-trained image recognition backbone, which transforms the model into a Fully Convolutional Network (FCN) capable of per-pixel labeling. Figure 9 shows an example of Fully convolutional network which efficiently learn to make dense predictions for per-pixel tasks like semantic segmentation[7]. For this purpose, the pre-trained MHP segmentation model, which is based on the 21-class FCN-ResNet18 network and has been trained on the MHP v2.0 dataset [8], will be used. It accepts input images of 512×320 resolution and provides output at a refresh rate of $34\,\mathrm{fps}$ with an accuracy of 86.5%.

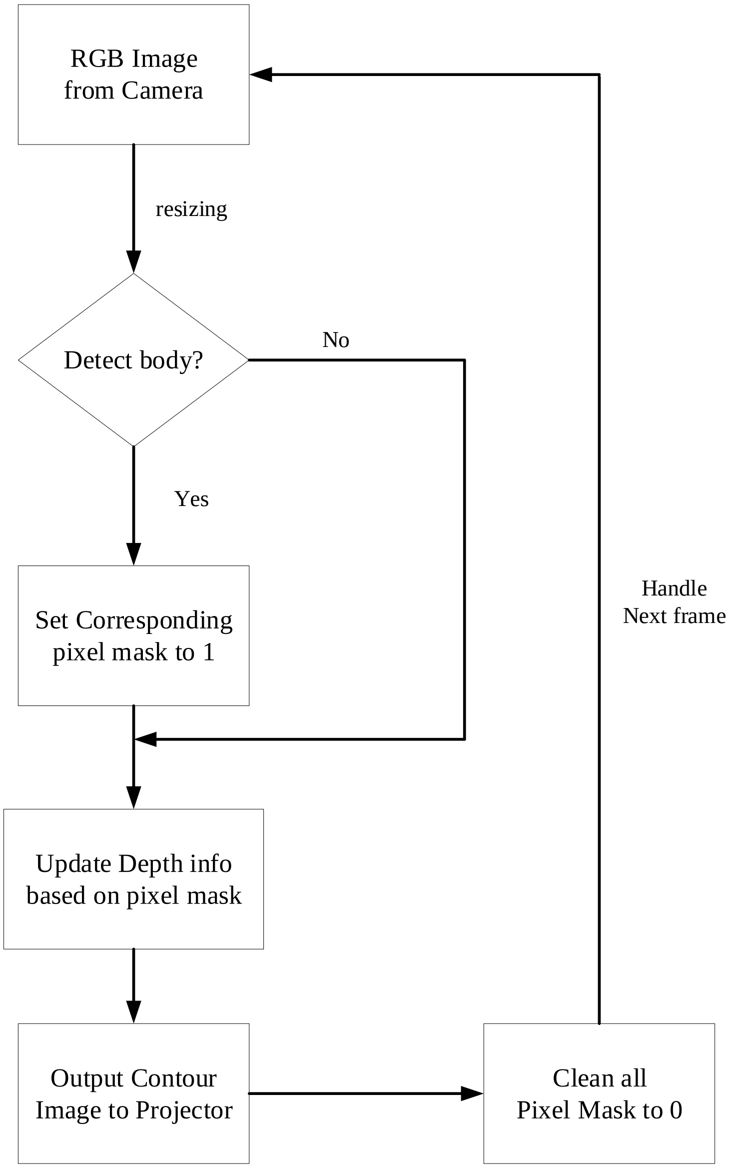


Figure 8: Body Detection Module Flowchart

Topography Rendering The depth information retrieved from Kinect V2 camera is a 8-bit grayscale image. The depth information is encoded in millimeters. The depth information is used to construct a topography map. The topography map is a 2D array with the same dimension as the depth information. The topography map is constructed by mapping the depth information to the height of the sand surface. The height of the sand surface is calculated by subtracting the depth information from the maximum depth value. We plan to use linear interpolation between two colors A and B with N degrees and get the color at certain height $gradient = A + \frac{B-A}{step} * N$ or use a lookup color table to convert height into color. After this, we could have a color gradient on the topography map. Based on depth information, contours are generated and projected onto the sand surface.

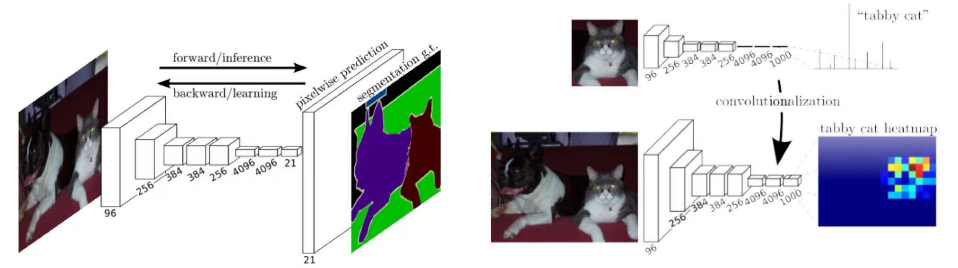


Fig. 1. Fully convolutional networks can efficiently learn to make dense predictions for per-pixel tasks like semantic segmentation.

Fig. 2. Transforming fully connected layers into convolution layers enables a classification net to output a spatial map. Adding differentiable interpolation layers and a spatial loss (as in Figure 1) produces an efficient machine for end-to-end pixelwise learning.

Figure 9: A FCN Model example

The contours are projected with different colors to represent different heights. The topography map is then projected onto the sand surface by the display subsystem.

The color table we choose to use is from the Generic Mapping Tools (GMT) software [9] as shown in Figure 10. GMT is a collection of tools for manipulating geographic and Cartesian data sets and producing illustrations ranging from simple x-y plots via contour maps to artificially illuminated surfaces. It includes GMT color tables that are widely used in the scientific community. We believe that the GMT color table is suitable for our project as it is widely used and has a wide selection of colors, ensuring that the projected topography map is clear and easy to understand.

Save and Load Topography We plan to build an interactive website that enables users to take a snapshot of a sand model and restore it at a later time. To achieve this, we equipped the Jetson Nano with an REALTEK 8822CE wireless network card. The website can be hosted directly on the Jetson Nano, and users can access the website on the same network via a specific hostname and port.

To facilitate file management, we intend to implement a simple database that records each snapshot's time and the file directory. Clicking the save button will trigger an insert SQL to the database, whereas clicking the load button will query the database, presenting the user with a table of saved models from which to choose.

Requirement	**Verification**
The body detection module should be able to process images at a rate of 30 fps. And the latency should be negligible for human eyes.	Set up a test environment where the body detection module processes a continuous stream of images above 30 fps and count number of images processed in a certain period of time.
The body detection module should predict the human body with an accuracy higher than 80% per pixel.	Prepare several labeled images and run the body detection on test datasets to calculate its accuracy.

The topography rendering module should be able to construct a topography map from depth information and project the topography map onto the sand surface.	Build sand models in different shapes and check if the contour line and color is correctly assigned.
The system must ensure that the wireless connection, facilitated by the REALTEK 8822CE network card, is stable and can support multiple users. Also, the database shoud be updated correctly when multiple users are saving models or loading models at the same time.	Use more than 5 devices to access the website at the same time and each do operations like reloading homepage, saving or loading a model. Then check the connection stability and see if the save and load operations are correct. Each user connected wirelessly should not experience operation delay longer than 3 seconds.

Table 2: Processing Subsystem RV Table

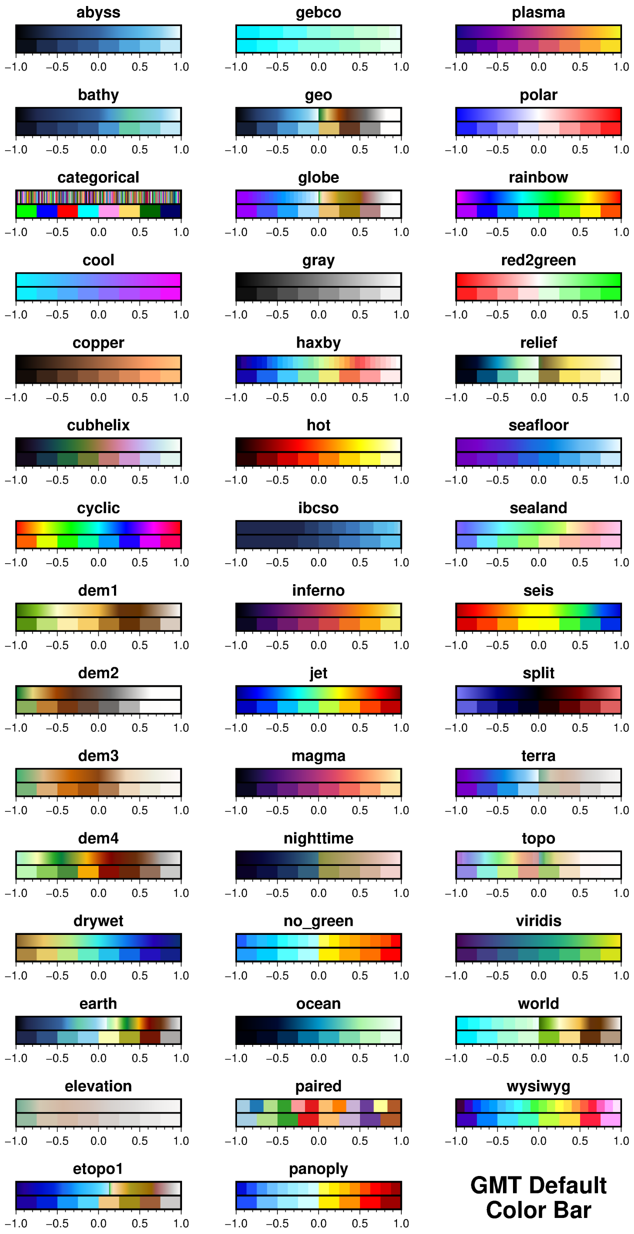
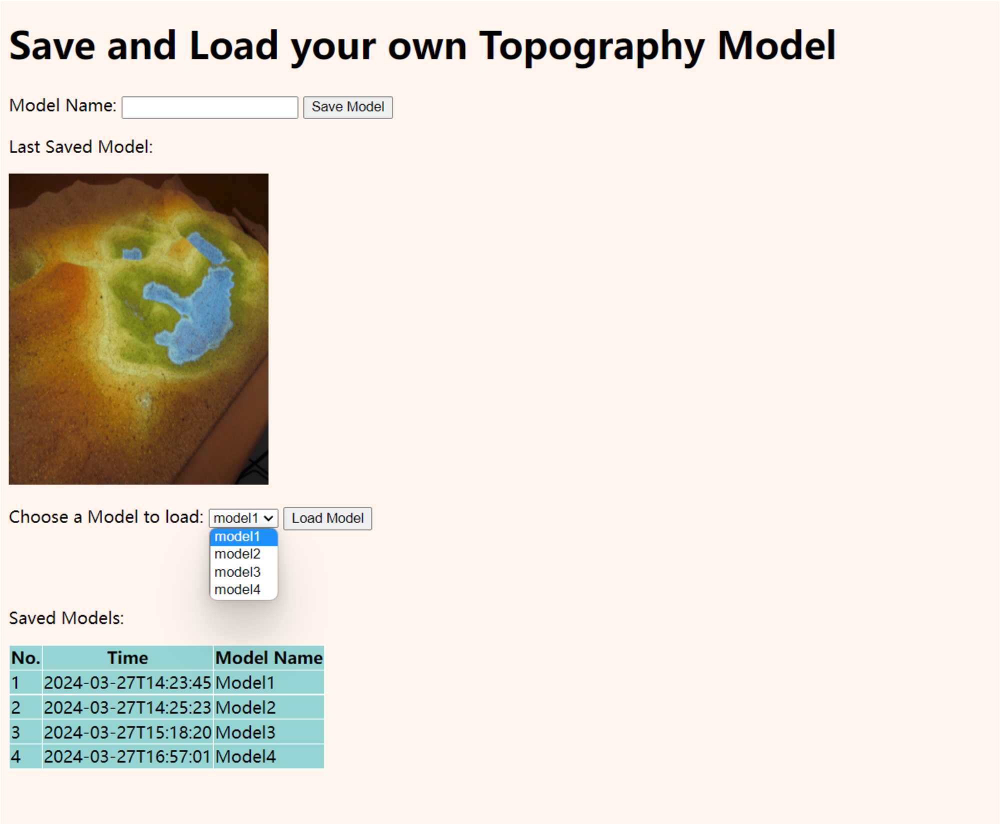


Figure 10: Sample GMT Color Table

2.1.4 Display Subsystem

Wireless Display The website has two primary functions, represented by two buttons: ”Save” and ”Load” as shown in Figure 11. The ”Save” button allows users to preserve the current state of the sand model, saving its depth information as a file. Conversely, the ”Load” button enables users to retrieve and display any previously saved model. To assist with spatial orientation, the system employs a projector: displaying red to indicate areas where the sand level is lower than the model (signifying the need for additional sand), and blue where the sand exceeds the model's height (indicating areas that need to be leveled).



Save and Load your own Topography Model

No.	Time	Model Name
1	2024-03-27T14:23:45	Model1
2	2024-03-27T14:25:23	Model2
3	2024-03-27T15:18:20	Model3
4	2024-03-27T16:57:01	Model4

Figure 11: Mock UI of the website

Projection Display The projector in display subsystem is responsible for projecting the topography map onto the sand surface. Considering that we are projecting onto sand, the display subsystem should be able to project the topography map with high luminance and low latency. To mount the projector lower for an easier installation and match the camera's field of view, we aim for a short throw projector. For this, we choose to use a high luminance short throw projector from EPSON with a resolution of $1024 \times 768\,\mathrm{pixels}$ and zoom factor of 0.31 in horizontal direction and 0.41 in vertical. It has a refresh rate of $60\,\mathrm{fps}$ and 2600 ANSI lumens. The projector connects with the processing unit through HDMI cable, which is compatible with our Jetson platform.

Figure 12: EPSON EB-CU600X Projector

Calibration Algorithm The calibration algorithm should be able to track the projected image alignment with the sandbox. The calibration algorithm should be able to adjust the alignment of the projected image with the sandbox in real-time. The calibration algorithm should be able to adjust the alignment of the projected image with the sandbox according to the height of the sand surface.

According to the specs of the projector, the projector has a zoom factor of 0.31 in horizontal direction and 0.41 in vertical. The calibration algorithm should be able to adjust the alignment of the projected image with the sandbox according to the zoom factor of the projector. Based on a throw distance simulator provided by EPSON [10], here is a graph showing the zoom factor of the projector:

Based on this, we can adjust the alignment of the projected image with the sandbox according to the zoom factor of the projector. An elevated point on the sand surface would be projected to a point further away from the actual point and the projector. The calibration algorithm should be able to adjust the alignment of the projected image with the sandbox according to the height of the sand surface.

Requirement	**Verification**
The calibration algorithm should be able to track the projected image alignment with the sandbox and the alignment error should be less than $1\,\mathrm{cm}$ when installed with our sandbox.	Use the calibration algorithm to track the projected image alignment with the sandbox. Put boxes with known dimensions on the sandbox and project the image. Check if the offset between the projected image and the boxes is within the acceptable range.

Table 3: Display Subsystem RV Table

2.1.5 Auto Focusing Subsystem

Considering that we would need to adjust the focus of the projector according to the height of the sand surface and the projector only allows for manual focusing through a lever shown in Figure 14, we would need to add a stepping motor to control the projector's lever automatically. The step motor connects with the focusing lever on the projector through a customed connector on a sliding table as shown in Figure 15. The stepping motor would be controlled by the processing unit and connected with the lever to control its position. The processing unit would use the depth information from the sensor subsystem to adjust the focus of the projector according to the height of the sand table.

We plan to use a 28HS28 two-phase stepping motor with a $1.8°$ step angle and a holding torque of $0.08\,\mathrm{N}\cdot\mathrm{m}$. It needs $350\,\mathrm{mA}$ current and $4.2\,\mathrm{V}$ to operate. It is installed on a linear sliding table with $50\,\mathrm{mm}$ stroke. The stepping motor connects with the processing unit through a drive board. The drive board connects with the processing unit through GPIO pins and receives PWM signal from the processing unit. The Jetson Nano has pin assignments as shown in Figure 16, including GPIO pins that can be configured to be PWM output.

The drive board connects with the stepping motor through a 4-pin connector. We will use the ULN2003 chip to drive the stepping motor. The ULN2003 chip is a high-voltage, high-current transistor array. Each channel of the chip can drive up to $500\,\mathrm{mA}$ of current, which satisfies the need of our motor. This chip also contains internal clamp diodes to dissipate voltage spikes [11]. The circuit diagram is shown in Figure 17. We put LED lights on the stepping motor to indicate the status of the motor.

Requirement	**Verification**
The auto focusing algorithm should be able to adjust the focus of the projector according to the height of the sand surface.	Use the auto focusing algorithm to adjust the focus of the projector according to the height of the sand surface. Adjust the height of sand table and project image with thin lines with one pixel wide onto it. Check if the projected lines are clear.

Table 4: Auto Focusing Subsystem RV Table

2.1.6 Powering Subsystem

The powering subsystem is responsible for providing power to the sensor, processing, and display subsystems. The powering subsystem should be able to provide power to the sensor, processing, and display subsystems with sufficient power and voltage. The

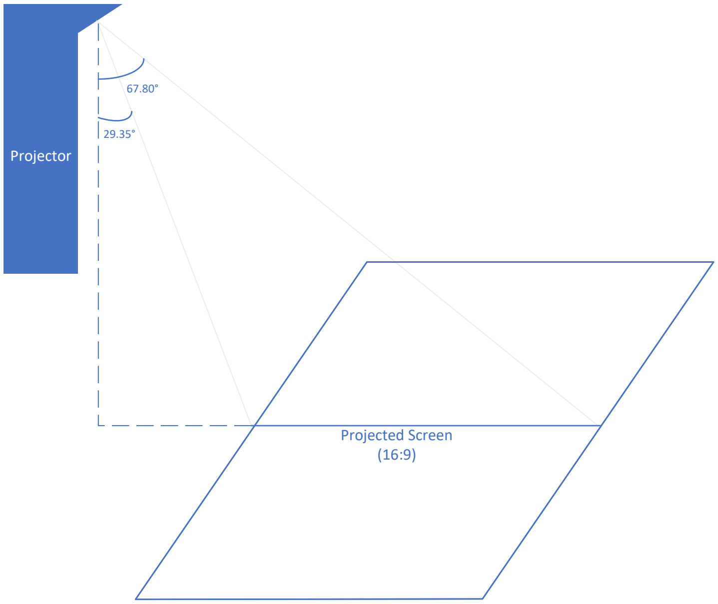


Figure 13: Zoom Factor of EPSON EB-CU600X Projector

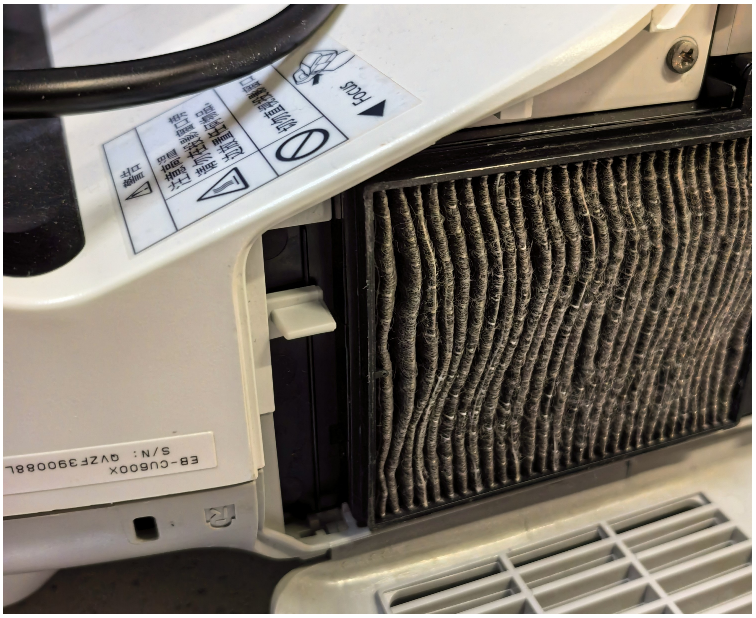


Figure 14: Focus Lever on EPSON EB-CU600X Projector

powering subsystem should be able to provide power to the sensor, processing, and display subsystems with high reliability and high safety.

The Kinect sensor and projector take $220\,\mathrm{V}$ AC power, while the processing unit and the drive board of stepping motor takes $5\,\mathrm{V}$ DC power. We have a $220\,\mathrm{V}$ to $5\,\mathrm{V}$ power converter which is verified that can safely convert the $220\,\mathrm{V}$ AC power to $5\,\mathrm{V}$ DC power and provide $20\,\mathrm{W}$ at maximum for the processing unit and the drive board of the stepping

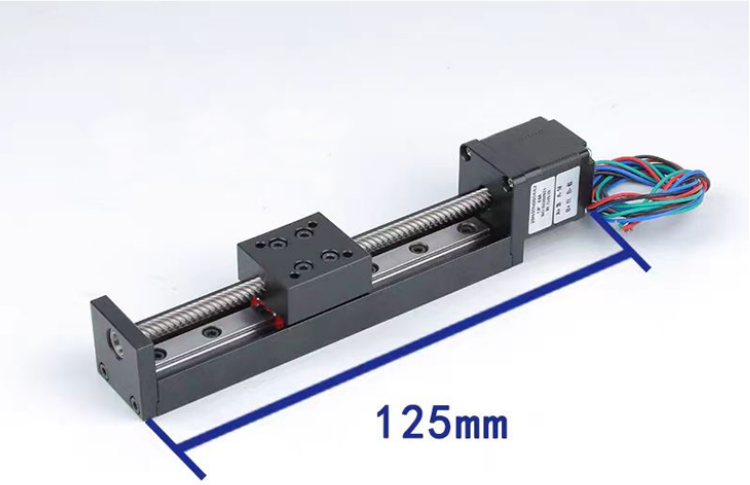


Figure 15: Stepping Motor and Sliding Table

motor. The Jetson Nano takes $5\,\mathrm{V}$ DC power and $2\,\mathrm{A}$ current at maximum. The stepping motor takes $4.2\,\mathrm{V}$ DC power and $0.35\,\mathrm{A}$ current. The power consumption of these two parts is within the power supply's capacity.

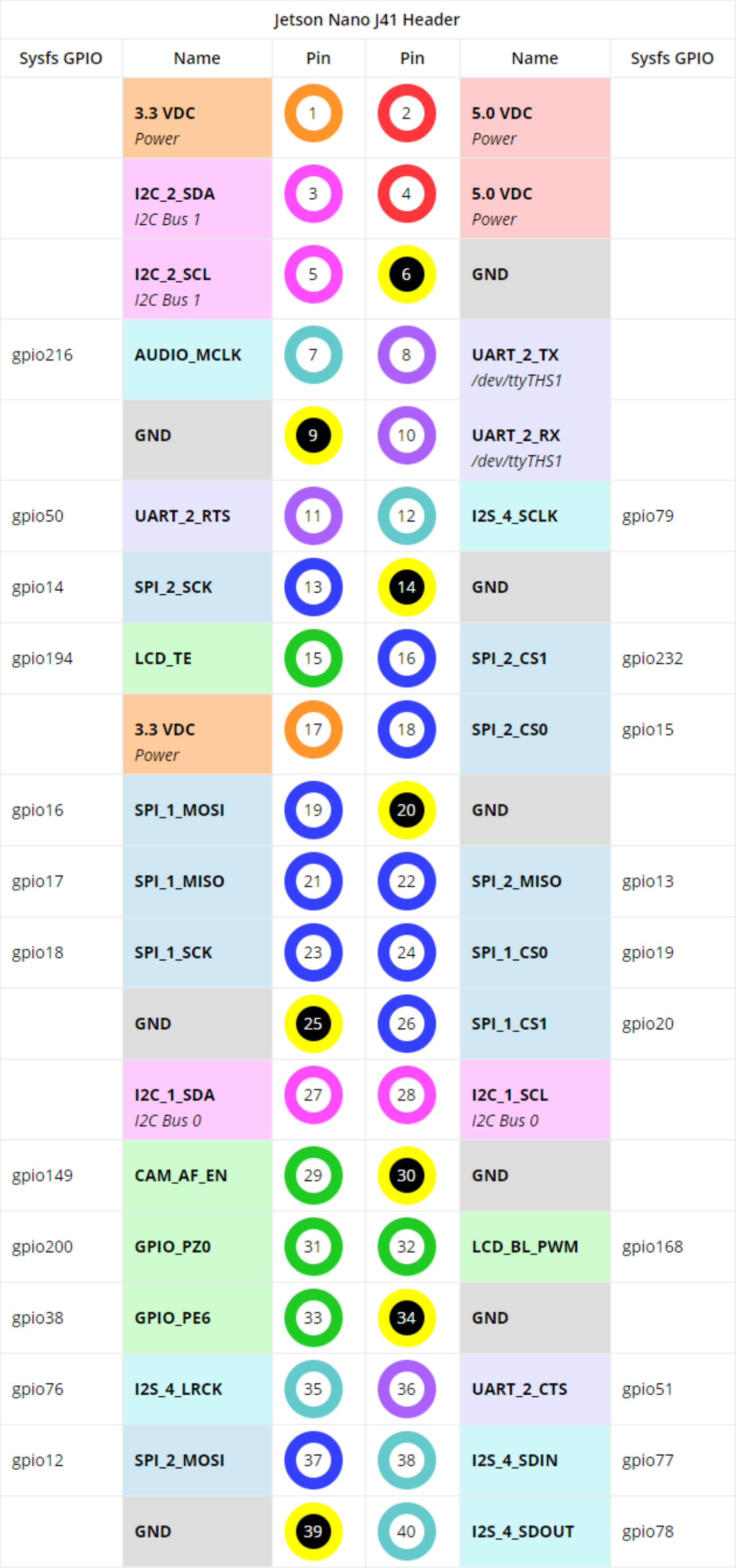
We will use a power strip with fuse protection to connect the Kinect sensor, projector, stepping motor and processing unit to one plug.

Requirement	**Verification**
The powering subsystem should be able to provide power to the sensor, processing, and display subsystems with sufficient power and voltage.	Connect the sensor, processing, and display subsystems to the powering subsystem. Check if the sensor, processing, and display subsystems are powered on. Put all subsystems at work for more than an hour, check if sufficient power is provided and no components failed.

Table 5: Powering Subsystem RV Table

2.1.7 Structure Subsystem

The sandbox was designed to store the sand and connect all the other parts. The main part of the sandbox is primarily composed of three components: the body of the sandbox, cover with hinge, and detachable part as shown in Figure 18. A hinge is used to connect the inside of two of the cover plates and between the cover plate and the box, ensuring that the cover plate can be folded and move freely. This facilitates the later work of the recovery system. A simple dovetail structure is utilized between the box and the detachable part. This decision is primarily based on the consideration that when the sandbox is placed horizontally on the desktop, the connected part will not be subjected to significant



Jetson Nano J41 Header

Sysfs GPIO	Name	Pin	Pin	Name	Sysfs GPIO
	3.3 VDC *Power*	1	2	**5.0 VDC** *Power*	
	I2C_2_SDA *I2C Bus 1*	3	4	**5.0 VDC** *Power*	
	I2C_2_SCL *I2C Bus 1*	5	6	**GND**	
gpio216	**AUDIO_MCLK**	7	8	**UART_2_TX** */dev/ttyTHS1*	
	GND	9	10	**UART_2_RX** */dev/ttyTHS1*	
gpio50	**UART_2_RTS**	11	12	**I2S_4_SCLK**	gpio79
gpio14	**SPI_2_SCK**	13	14	**GND**	
gpio194	**LCD_TE**	15	16	**SPI_2_CS1**	gpio232
	3.3 VDC *Power*	17	18	**SPI_2_CS0**	gpio15
gpio16	**SPI_1_MOSI**	19	20	**GND**	
gpio17	**SPI_1_MISO**	21	22	**SPI_2_MISO**	gpio13
gpio18	**SPI_1_SCK**	23	24	**SPI_1_CS0**	gpio19
	GND	25	26	**SPI_1_CS1**	gpio20
	I2C_1_SDA *I2C Bus 0*	27	28	**I2C_1_SCL** *I2C Bus 0*	
gpio149	**CAM_AF_EN**	29	30	**GND**	
gpio200	**GPIO_PZ0**	31	32	**LCD_BL_PWM**	gpio168
gpio38	**GPIO_PE6**	33	34	**GND**	
gpio76	**I2S_4_LRCK**	35	36	**UART_2_CTS**	gpio51
gpio12	**SPI_2_MOSI**	37	38	**I2S_4_SDIN**	gpio77
	GND	39	40	**I2S_4_SDOUT**	gpio78

Figure 16: Jetson Nano Pinout

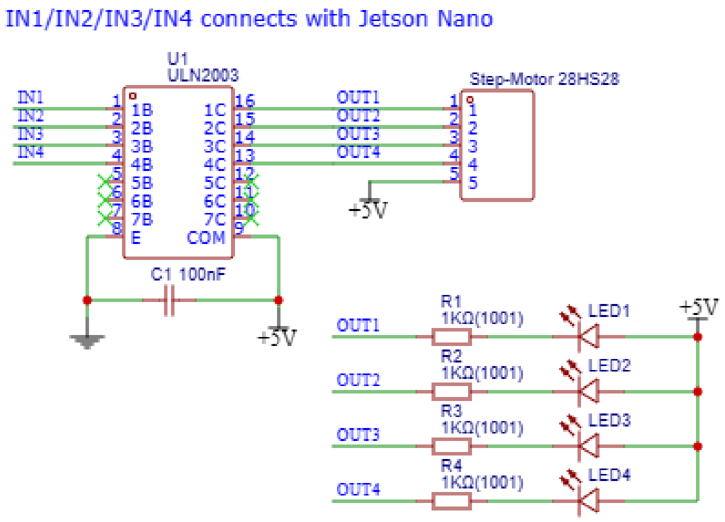


Figure 17: Step Motor Drive Board

force. Therefore, the ease of separation of detachable parts is deemed more important than the stability of the connection. The detachable part serves to place the projector and secure the camera. The projector can be embedded in the top $160 \times 380 \times 10\,\mathrm{mm}$ groove, ensuring ease of use and stability. The sensor will be attached to the middle of the hollow side by a grippable bar. The hollow part in the middle is designated for storing the processing system and the powering system, ensuring that the final powering system only requires a wire sticking out of the box to supply energy to the entire system. Simultaneously, this detachable part enables our electronic devices to be used independently from the original sandbox, making our product suitable for more scenarios.

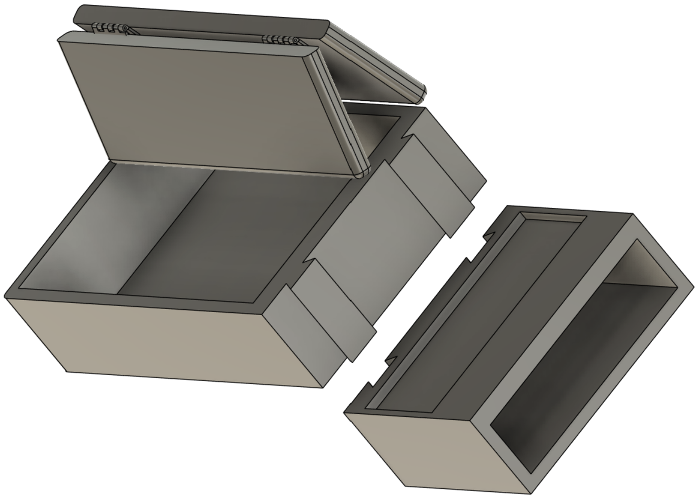


Figure 18: Overall Structure Design of the Sandbox

ABS plastic will be used to make the entire sandbox through 3D printing, except for the hinge, which will be purchased as a finished product made of alloy. After calculation and simulation, it has been determined that ABS plastic is sufficient to meet the requirements and ensure safety. Further explanation on this matter will be provided in a later section.

Recovery System The main function of this system is to quickly restore the used sand table conveniently. Since the use of electric devices would complicate the use and maintenance of the sandbox, a shovel of special construction has been designed to achieve this purpose. The structure of the shovel is shown in the Figure 20. The principle is that when pushed forward, excess sand is shoveled into the shovel and stored in the hollow section in the middle, while the sand stored on return is filled through the hole in the bottom to the empty place. The shovel will be placed in a guide rail as shown in Figure 19, and the upper end is connected to the edge of the sandbox cover plate using a soft plastic sheet. This allows the user to restore the sand surface by opening and closing the sandbox only once. Additionally, the pure human operation of the recovery system can prevent users from being hurt, which will undoubtedly be more convenient and safer.

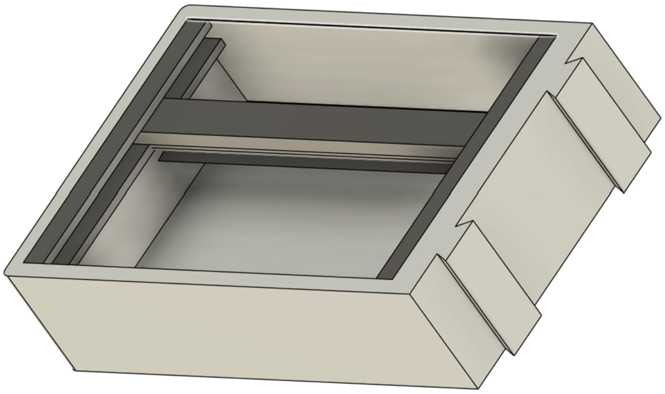


Figure 19: Design of Guide Rail for Shovel

Requirement	**Verification**
Design a sturdy and stable support structure capable of safely holding the weight of the AR sandbox ($25\,\mathrm{kg}$) and the projector set($5\,\mathrm{kg}$) without risk of collapse or instability during use. The weight of the sandbox and projector should be distributed evenly across the support structure.	Conduct load testing to verify that the support structure can safely withstand the combined weight of the AR sandbox, sand and the projector set. Apply enough sand to simulate real-world usage scenarios. Check for any signs of stress concentration or uneven loading that could compromise stability.

Ensure that the design minimizes potential hazards for children interacting with the AR sandbox. Eliminate sharp edges, protruding components, or other features that could cause injury.	Perform a safety inspection of the support structure to identify any potential hazards or safety concerns. All edges should be rounded, sharp corners be eliminated, and there are no small parts that could pose choking hazards to children.
The projector set on top should be separable, and the separable part should be able to be used separately and can adapt to different use environments and scenarios.	Conduct a practical test where the projector is detached from the support structure. Verify that the separable part functions independently and can be easily moved to different locations or setups as needed. Then assess the reattachment process to confirm that it can be securely and quickly reconnected to the support structure without compromising stability or safety.
The restoration system should achieve the re-tiling of the sand surface in a simple way.	Conduct a practical test where the sand is deliberately disturbed or unevenly distributed. Use the restoration system and observe its ability to re-tilt the sand surface to a uniform level. Then evaluate the consistency and smoothness of the restored sand surface to by projecting topography onto the sand.

Table 6: Structure Subsystem RV Table

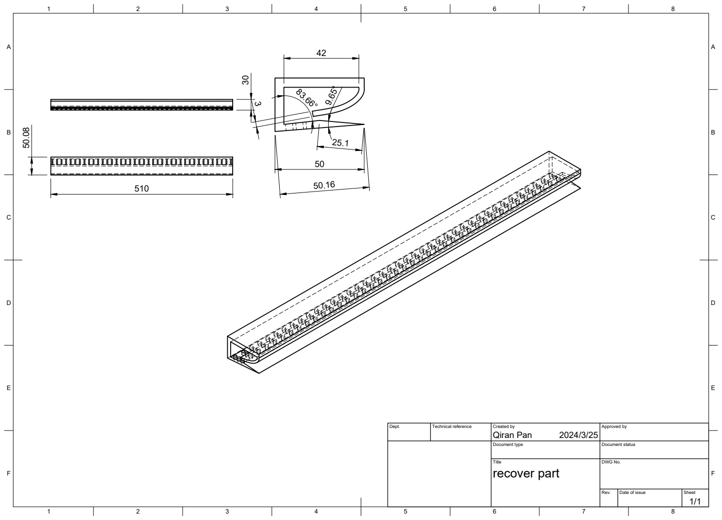


Figure 20: Design of the Sandbox's Shovel

2.2 Tolerance Analysis

Processing Subsystem

The key component of our design is the speed of real-time topography rendering considering the interference of users' heads and hands. The projector can output 1920×1080 at $60\,\mathrm{Hz}$. As we aim to reach a refresh rate of at least $30\,\mathrm{Hz}$ with low latency, the processing time of each topography frame should be less than $1000/30 = 33.3\,\mathrm{ms}$. With human body detection and hand gesture detection, the processing subsystem needs to have fast enough algorithm and hardware computation power that finish the computation of each frame within $33.3\,\mathrm{ms}$. But as the resolution of RGB and depth image would not be very high, around 1280×720 would be enough, when designing a sandbox for 2 or 3 kids to use in normal conditions. Thus, we think the risk would be justified by the actual amount of data we need to process.

The refresh rate of our projector is highly depend pre-processing procedure on the receiving side. Our depth data is received in the form of 8 bits, and raw data goes into Jetson Nano. The Jetson Nano has 4 GB of 64-bit LPDDR4 memory, which is more than enough for pre-processing depth information from 8-bit binary inputs and for drawing projected images with resolutions up to 1920×1080 For 8-bit binary depth information processing, we will firstly use `median_filter` to remove `salt_and_pepper` noise, the processing time is $280.56\,\mathrm{ms}$ for a 512*512 test image, and secondly, we need to blur the input depth information in order to make it easier to colorize in the next step. We choose the simple Dehaze algorithm and the processing takes $1.0827\,\mathrm{s}$.

Structure Subsystem

We think it is necessary to carry out tolerance analysis on the mechanical structure of the sandbox. We have confirmed that the model using ABS plastic can fully meet the functional needs of the AR sandbox. The sample we used was produced using 3D printing, which can almost perfectly reproduce the CAD model. However, such accurate production is difficult to achieve in actual production. Whether it is the production method of 3D printing, or the selection of ABS materials will increase the cost of the product. Therefore, our tolerance analysis focuses on whether structural errors and the influence of different materials on the performance of our products are acceptable.

First of all, in actual production, the production method with a high probability is injection molding. This is suitable for fast, large-scale production, and can effectively reduce costs. However, the biggest drawback of the injection molding process is that the accuracy is not as good as 3D printing. According to the data, the typical tolerance for injection molding is usually +/-$0.1\,\mathrm{mm}$, while the very strict tolerance is +/-$0.025\,\mathrm{mm}$ [12]. In order to ensure the results were convincing, I enlarged the tolerance of $0.1\,\mathrm{mm}$ tenfold in the analysis. This means that the thickness of all parts of the model will be reduced by $2\,\mathrm{mm}$.

The second is the choice of materials. Even though acrylonitrile butadiene styrene (ABS) is a good choice, the significantly lower price of polystyrene (PS) and polypropylene

(PP) for the same weight can undoubtedly reduce production costs. It is worth noting that the injection molding process is also suitable for acrylic (PMMA), nylon polyamide (PA), polycarbonate (PC), polyethylene (PE), thermoplastic elastomer (TPE), Thermoplastic polyurethane (TPU) and other common materials. Some of these materials are too expensive (e.g., PE, whose price is almost 1.5 times of ABS), while others have obvious defects in structural strength (e.g., TPE is too ductile). So we don't take that into consideration. For PP and PS, we ignore the process of filling glass fibers to increase their strength. Although this approach is often used in daily production, it reduces the universality of our analysis.

To sum up, the model of thinner PP and PS materials will be simulated to confirm that the design exhibits very good tolerance. The part chosen for analysis is the separable part with the most hollow sections, the highest pressure, and the greatest susceptibility to external disturbances. If this part performs adequately, it indicates that the other parts are functioning effectively.

Starting with a control group, which represents what is considered a perfect model, an equivalent force of $5\,\mathrm{kg}$ was added to the groove to simulate the weight of the projector being used. The force applied to the edge consists of two parts. Firstly, this position will hold a camera, and secondly, after analysis, it is determined that this position is the most prone to deformation, making it the most suitable point for simulating external forces. As shown in Figure 21 and 22, a downward force of $500\,\mathrm{N}$ was applied to this position to simulate the worst-case scenario. It is found that under such conditions, the pressure and deformation of the detachable part remain negligible.

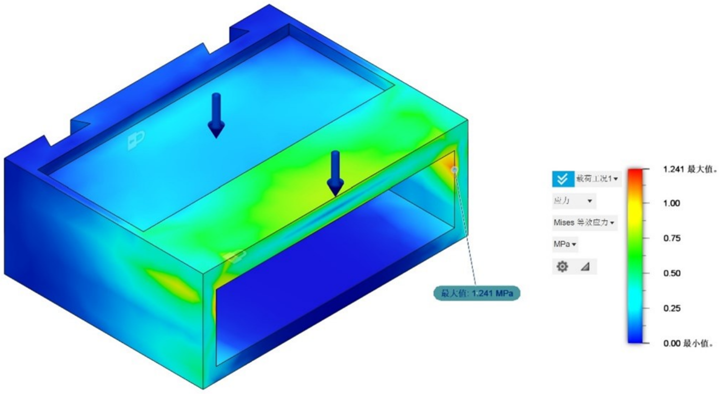


Figure 21: Pressure Analysis on ABS Material Standard Part

Next is the simulation results of PP material with error model. According to the results shown in Figure 23 and 24, it can be concluded that under this condition, even if the value of the deformation increases a lot compared with the original, it is still small enough to be ignored for the whole model.

Finally comes to the simulation results of PS material in Figure 25 and 26 and there are errors in the model. We are pleasantly surprised to find that the PS material shows increased structural strength. This proves that the design of the structure is completely

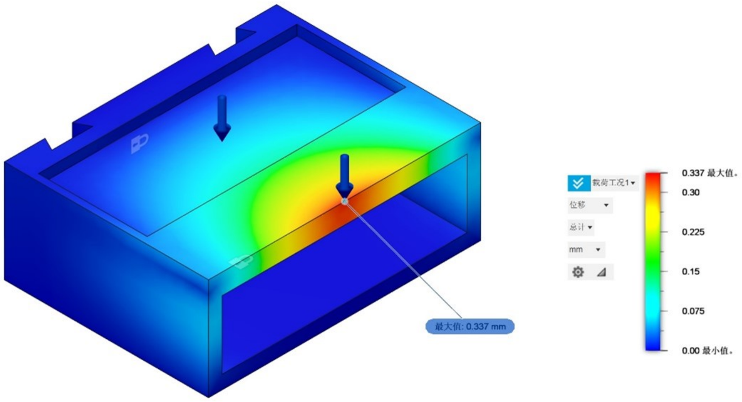


Figure 22: Deformation Analysis on ABS Material Standard Part

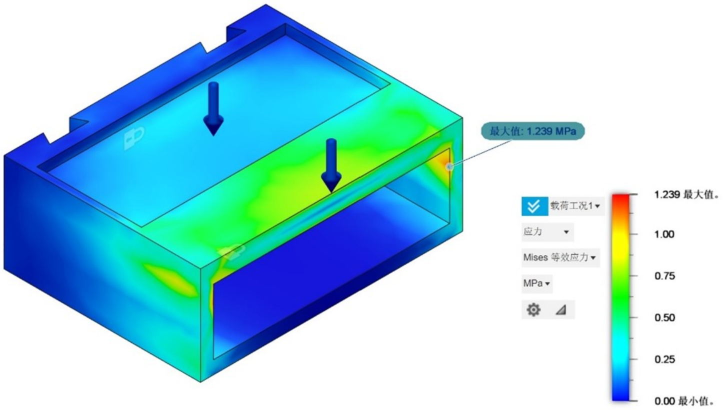


Figure 23: Pressure Analysis on PP Material Defects

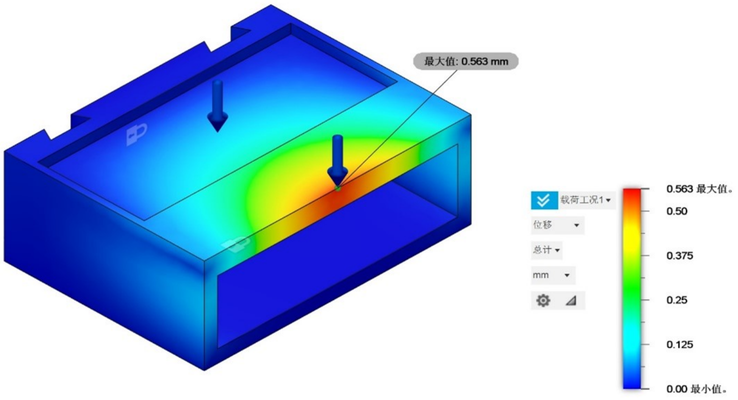


Figure 24: Deformation Analysis on PP Material Defects

feasible.

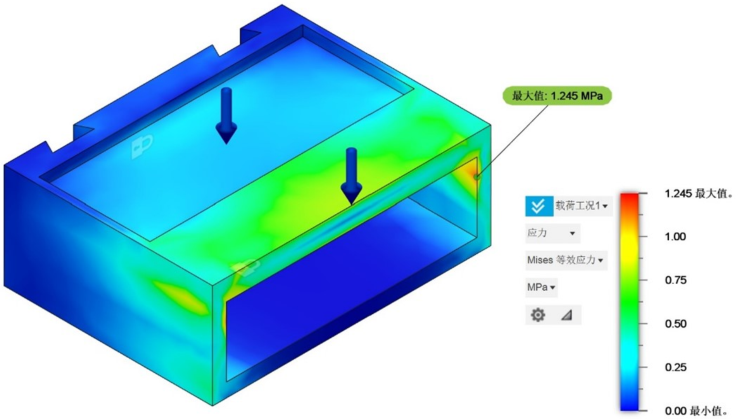


Figure 25: Pressure Analysis on PS Material Defects

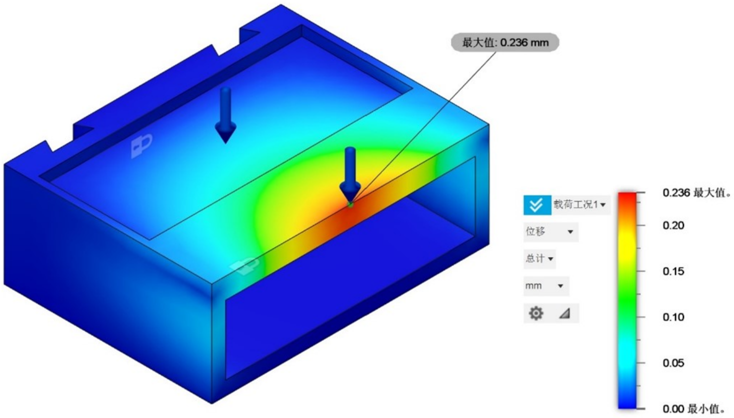


Figure 26: Deformation Analysis on PS Material Defects

In conclusion, we believe that the implementation feasibility of our design is very strong. It can tolerate errors generated in industrial production and can also be applied to a variety of materials. So overall it was a very successful design. However, there is one more thing to add about the selection of materials. An important audience for our sandbox design is children, and safety and health factors must be fully considered. Although PP and PS are very satisfactory in terms of strength and price, there are some defects in physical properties. PP and PS are extremely easy to burn, and PP will decompose harmful aromatic hydrocarbons such as benzene and toluene at high temperatures [13]. Therefore, from a designer's point of view, I still recommend the use of ABS plastic.

3 Cost and Schedule

Here we will discuss the cost and present a schedule of our work.

3.1 Cost

The cost of our project consists mainly of the cost of the hardware and the cost of labor.

3.1.1 Labor

The labor cost is calculated based on the assumed salary of \$20 per hour. There are four members in our team. The time spent on the project for each people is estimated to be 25 hours per week. The total duration for this project is 10 weeks. Thus, the total labor cost would be:

$$\text{Labor cost} = 20 \times 25 \times 10 \times 4 = \$20000$$

3.1.2 Components

The cost of the components is shown in Table 7. The non-standard parts mainly include the structure part, which we plan to produce in the school laboratory by 3D printing. The material will be ABS plastic, and the filling rate should be between 30% and 50%. Since it has not yet been officially put into production, it is difficult for us to estimate the exact quantity of consumables. Therefore, we will not include the cost of consumables in the cost estimate.

name	description	manufacturer	part #	quantity	cost (CNY)
JETSON NANO B01 with 5V, 4A power supply	NVIDIA Jetson Nano developer motherboard	NVIDIA	B01	1	1199
Children's Plastic Sandbox	sandbox to support the sand	Foshan Liasheng Plastic Manufacturing Plant	No.8 ($40\,\text{cm}$ * $80\,\text{cm}$ * $12\,\text{cm}$)	1	59
EPSON CU600X Ultra Short Throw HD Projector	Projector used to project contour maps onto a sand table	EPSON	CU600X	1	584.5

Microsoft Kinect V2 camera	Gather images of the sandbox as well as depth information	Microsoft	V2	1	770
RTL 8822CE Wireless Network Card	network card for wireless connection for Jetson Nano	REALTEK	8822CE	1	25
Delta electronics brushless fan	fan for cooling the Jetson Nano	Delta Electronics	AFB0412VHA	1	5
superfine river sand	Placed in a sandbox for children to use	TIAN-SHISHUIZU	unknown	3*5 kg	53.4
Screw Type Terminal Block	Fixed input and output wires	KEFA	C474881	4	2.5
Dual Brushed DC Motor Drive Circuit	Stepper motor driver chip	mixic	C5119044	1	1.682
Desktop retractable stand	Potential projector support components	Chenxin Digital Accessories	1/4 inch - external teeth	1	23.4
Linear Sliding Table with Stepper Motor	Stepper motor for adjusting the focus of the projector	Ouli Transmission	28 T6*1-50mm	1	85

Table 7: Cost of the Components

Total cost of the components is:

Component cost $= 1199+59+584.5+770+25+5+53.4+2.5+1.682+23.4+85 = 2809.02$

3.2 Schedule

starting date of each week	Haoze Gao	Haowen Zheng	Qiran Pan	Yiheng Zhang
25-Mar	choose step-motor and material for building physical structure	configure the processor and try to run a basic demo.	finalize structure design on the container and the supporter	try out some contour painting methods using Python. Study digital signal processing methods for processing depth data.
1-Apr	Collect data for training segmentation algorithm of body parts.	connect depth info with color and do a simple projection	combine projector and the sensor into a unified structure.	learn OpenCV in C++ about denoising and dehazing
8-Apr	do segmentation training	realize projecting contours onto sand	do physical testing on the models and build prototypes	write program that does ISP and do some testing
15-Apr	design PCB for motor control and write program on turning RGB color into auto-focusing control signal	build database for temporary contour storage	build the sandbox and the container	help build the container and the sandbox
22-Apr	solder PCB and route with step-motor	learn about wireless transmission protocol	build the supporting pillar and connect all structure together	configure power system and test on the active power
29-Apr	help organize parts in the container	write program on wireless transmission	organize parts in the container	write program on automatic recognition of projection range so that sandbox may be discarded

5-Jan	combine all parts, write script for final demo	combine all parts, write script for final demo	combine all parts, write script for final demo	combine all parts, write script for final demo
6-May	Mock demo	Mock demo	Mock demo	Mock demo
13-May	Final demo	Final demo	Final demo	Final demo
20-May	final individual design report	final individual design report	final individual design report	final individual design report

Table 8: Schedule of the Project

4 Ethics and Safety

4.1 Ethical Issues

High luminance projector would be energy-consuming. It is possible that the user forget to turn of the AR sandbox after use. This would bring potential environmental issue. As stated in ACM code of Ethics and Professional Conduct, "human well-being requires a safe natural environment. Therefore, computing professionals should promote environmental sustainability both locally and globally"[14]. In order to achieve this goal, we would explore ways to lower the power consumption during use and automatically detect the leave of users.

Also, consider the fact that people with different skin colors may have different reflection rates, the depth camera may not work well for people with dark skin. This would be a potential ethical issue and we need to consider seriously, as mentioned in IEEE Code of Ethics that "to treat all persons fairly and with respect, and to not engage in discrimination based on characteristics such as race, religion, gender, disability, age, national origin, sexual orientation, gender identity, or gender expression"[15]. We would consider adding more light sources to make the reflection more uniform.

4.2 Safety Concerns

There are a list of safety concerns towards our project:

- Electric shock: the projector and the sensor would be connected to power supply. The structure needs to be designed to prevent users from touching the wires and the power supply.
- PCB exposure: Using only PCB to design a 220 / 5 V power converter may not be the safest option. The inner connection on the foot may be broken, causing electricity leakage or short circuit.
- High luminance light: the projector would be high luminance to display clearly on sand considering sand as a diffuse reflection surface. Users might look directly to the projector accidentally that might cause harm to eyes. We would consider adding human eye detection function to turn off the projector when necessary.
- Laser: the depth camera use laser to help measure the distance. We choose an off-the-shelf depth camera whose laser safety has been verified by Microsoft and regulation authorities. The laser should be safe for human eyes.
- Step-motor malfunction: we will use the step-motor as part of the control system for auto focusing of the projector. As the whole system will be built from ground up and connected with projector with irregular shape, the step-motor may not be supported well, thus collapsing with PCB and the projector, or entangling into wires.
- Dust hazard: Fine sand may be inhaled by children when it is lifted into the air. In addition, fine dust may obscure the lenses of the projector and the camera, causing

interference with the input data and an unattractive projected image.

- Breach of structural integrity of the projector: In order to realize the auto focusing function, we will tear down parts of the purchased projector and punching holes on it, thus making the projector's air vents and the focusing lever exposed. This process may cause more dust entering the projector doing damage.
- Falls or deformation: the sand in the box could be heavy. After adding about 25 kg of sand into the box, center of mass will be lifted up, resulting in greater potential of falling down. The structure needs to withstand the weight of sand and consider users leaning on it. We performed simulation on the structure to ensure its stability shown in Figure 27 and Figure 28.

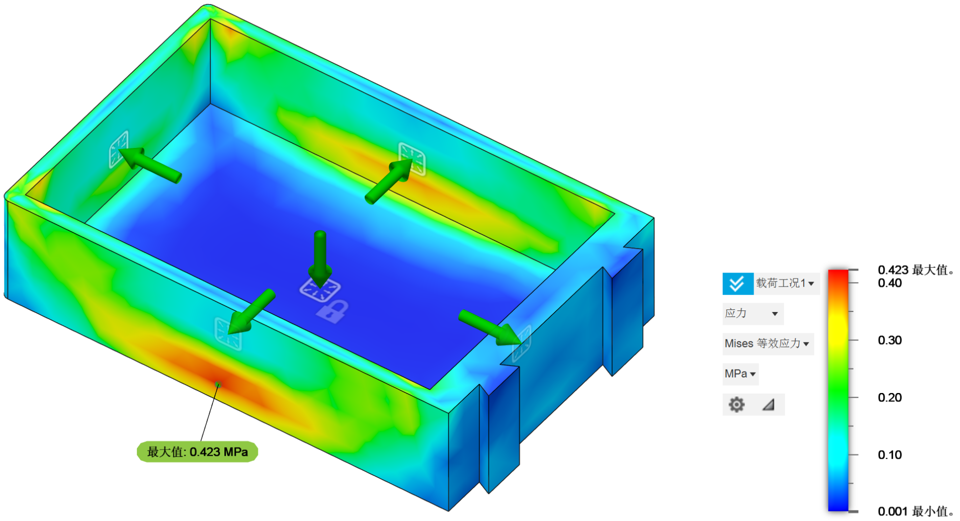


Figure 27: Bottom Pressure Simulation of the Sandbox with Sand in the Box

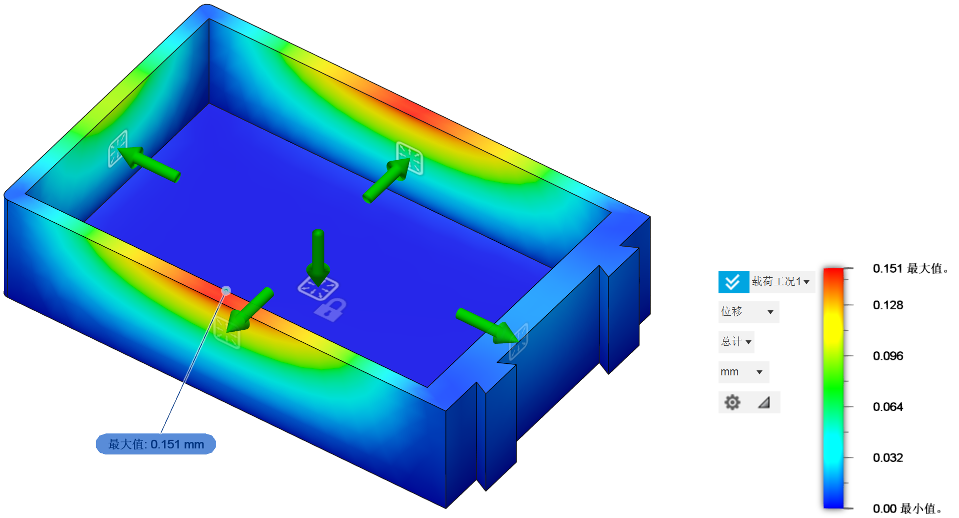


Figure 28: Side Pressure Simulation of the Sandbox with Sand in the Box

5 Conclusion

Our final goal is to have a redesigned AR sandbox that have a higher refresh rate, faster response, safer design and better human machine interaction than existing solutions. We wish it can be used for education and make kids interested in geology in an interactive way. We also hope that the AR sandbox can be used in other fields such as urban planning, water management, and environmental protection. We believe that the AR sandbox can be a useful tool for education and research in the future.

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