Documentation for Using VirT&R

Introduction

This document is intended to act as a more detailed ReadMe for using VirT&R (virtual teach and repeat). It will do this by guiding a new user through the required software dependencies and programs needed, as well as the steps involved in moving data products between them.

The entire process for making a virtual teach graph can be done on the ASRL asterisk remote server, and some effort has been made to ensure that the pipeline is as cohesive and integrated as possible (less need for moving files from place to place to be used/edited). Further effort is required, but it is an improvement over the working version used to produce results in the VirT&R paper.

The desired end result that will be added to this document, once achieved, is a single program where commands are entered in the terminal to perform all actions specific to the programs used with launch files all in one place rather than needing to use commands specific to those software programs in separate places.

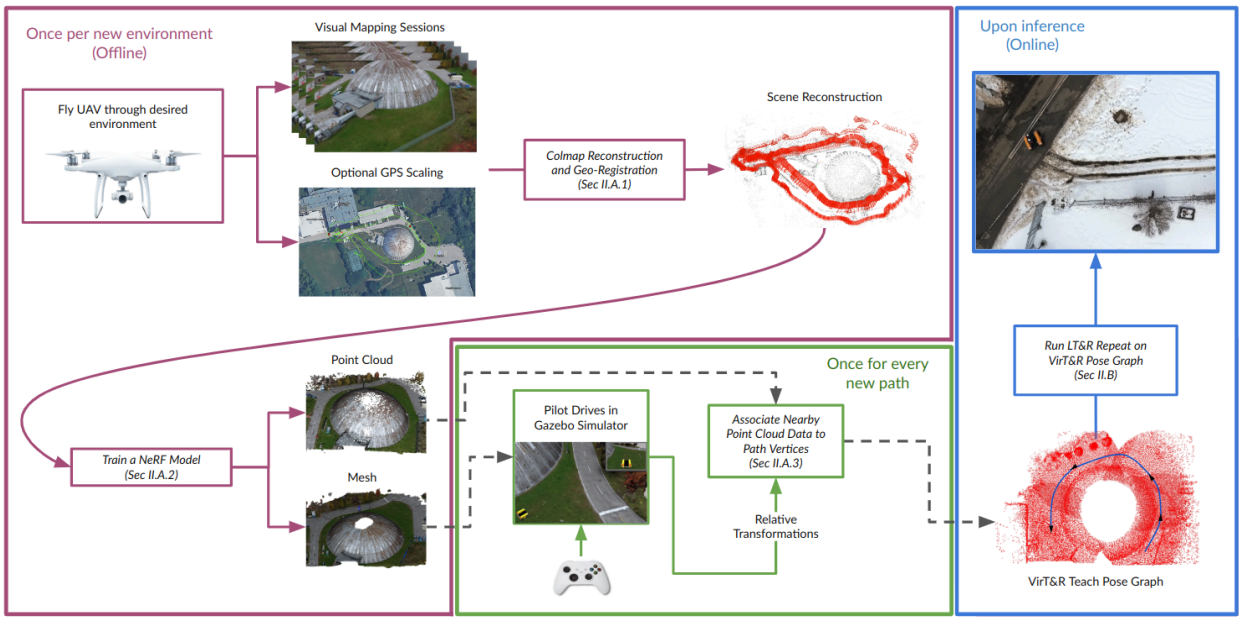
Required Software

The main software used in the VirT&R pipeline includes: **Visual Teach and Repeat** (virtual teach and repeat branch), **Gazebo**, **Blender**, **Colmap**, **NerfStudio**, and some custom scripts for initial data processing post UAV scene capture and gazebo path logging (that can be found in the virtual teach and repeat branch's package vtr_virtual_teach>scripts).

NOTE: Vtr3 is set up to use Ros Humble (Ros 2) and the specific Gazebo installation that is compatible with the model of the clearpath warthog requires Ros Noetic (Ros 1). Switching between these ros versions will be necessary and, to keep things simple, it is recommended to use two different terminals running the docker container so there is no switching back and forth. The procedure flows from using Ros 1 to Ros 2 and a switch should only need to be made once anyways.

Phases

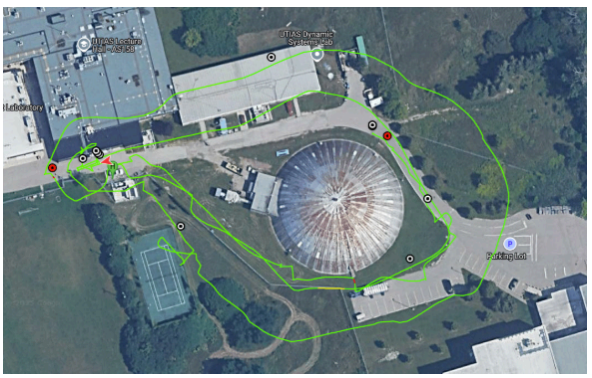
Making a virtual teach graph consists of three phases (not to be confused with the overall three phases of the whole VirT&R pipeline. The three phases, in order, are: UAV data processing,NeRF training, and point cloud/mesh path association for pose graph creation. These phases can be seen in **II.A.1**, **II.A.2**, and **II.A.3** of the VirT&R paper as shown in the overall pipeline diagram below.



Phase 1: UAV Data Processing

The following steps detail how to use and fly the DJI Phantom 4 UAV, extract frames and georegister them, and scale them down to be ready for NeRF training.

1. Unbox the DJI Phantom 4 UAV and connect your phone via usb cable to the controller (make sure you have the DJI Go 4 app downloaded).
2. Ensure there is an SD card in the UAV (slot on the side) with 20+ GB of space.
3. Go outside to a safe spot that isn't busy to set up the UAV by placing it on the ground and putting on the propellers.
4. Turn the UAV and controller on, then open the DJI Go 4 app.
    a. If you haven't already, go through the compass and IMU calibration steps in the menu at the top right corner of the screen.
5. Now that you are ready to fly (the UAV has 10+ satellites connected, is warmed up, and the lights are flashing green), move the UAV to the starting point you desire for scene capture if not already there.
6. Take off with the automated take off button.
    a. To fly the drone, the right joystick is used for translation (forwards/backwards/left/right) and the left joystick is used for elevation and yaw. The scroll wheel at the top left of the controller controls the camera angle.
7. The goal is to fly three passes around the desired environment to capture it sufficiently. There should be an inwards facing pass at 20 m, a nadir facing path over the robot's desired path at 15 m, and a POV facing path over the robot's desired trajectory at 5-10 m. This picture shows these three 'loops' through the environment around the Mars Dome at UTIAS (comes from a step further in the process) but is useful to show you what must be flown:

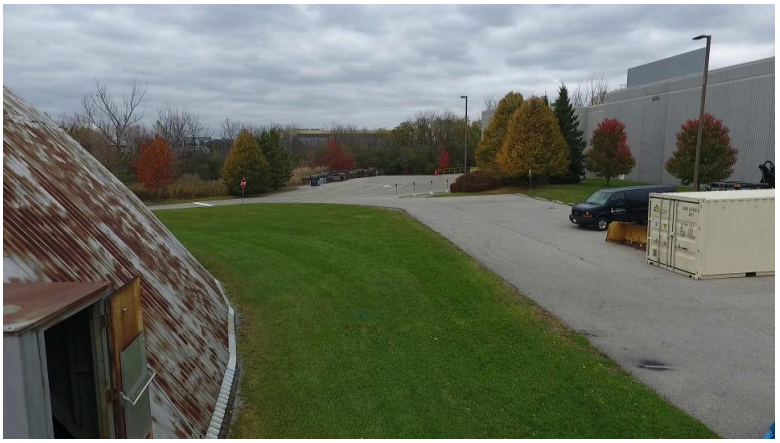


8. The first pass to fly is the ~20 m, 45 degree inwards facing pass.
    a. Identify the 'center' of your scene (ie. with the Mars Dome Loop, the center was roughly the center of the Mars Dome).
    b. Fly the drone up to around 20 m AGL (visually assess if there will be trees or terrain in the way at any time before flying the route).
    c. Tilt the camera until it is at a 45 degree angle, and spin the UAV using the yaw control so the center of the scene is being captured.
    d. Start the video recording.

e. Begin flying the UAV sideways in a curved path (doesn't need to be a perfect circle if there is some small area that sticks out that you want to capture) at a moderate and safe speed given your location and wind conditions.
f. Follow the UAV as you fly it, ensuring through the viewer on your phone that the center of the scene is mostly in view and your desired scene is being accurately captured.
g. Once you have returned to where you started, depending on battery life, land the drone, or prepare its position and camera angle for the next pass.

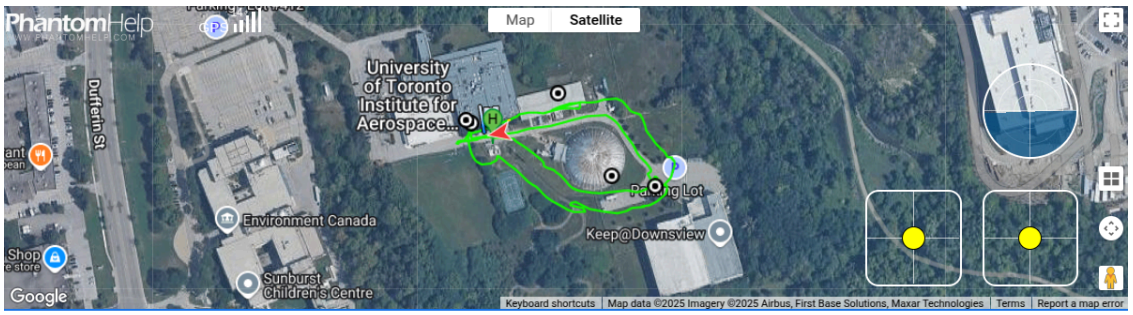
9. The next pass to fly is the 10 m forward, nadir facing pass.
    a. This pass uses the same 'center' of your scene and flies around it in a direction of travel that roughly follows what you want the UGV to follow.
    b. Fly the drone up to around 10 m AGL (visually assess if there will be trees or terrain in the way at any time before flying the route - make sure you're ready to adjust your course to give at least 1 m clearance for these obstacles).
    c. Tilt the camera until it is facing straight down, and spin the UAV using the yaw control so it is facing forward, ready to travel the path the UGV will follow.
    d. Start the video recording.
    e. Begin flying the UAV along your desired path around the center at a moderate and safe speed given your location and wind conditions.
    f. Follow the UAV as you fly it, ensuring through the viewer on your phone that the scene is being smoothly captured.
    g. Once you have returned to where you started, depending on battery life, land the drone, or prepare its position and camera angle for the next pass.

10. The final pass to fly is the 5-8 m forward, POV facing pass.
    a. This pass uses the same ‘center’ of your scene as well, but there is more flexibility in this pass to fly in/out/and around interesting features in the scene to capture it if need be (over hands, large pillars, narrow entrances etc). This pass also flies in the direction of travel that roughly follows what you want the UGV to follow.
    b. Fly the drone up to around 5-8 m AGL (visually assess if there will be trees or terrain in the way at any time before flying the route - make sure you’re ready to adjust your course to give at least 1 m clearance for these obstacles).
    c. Tilt the camera until it is facing straight forward, and spin the UAV using the yaw control so it is facing forward, ready to travel the path the UGV will follow.
    d. Start the video recording.
    e. Begin flying the UAV along your desired path around the center at a moderate and safe speed given your location and wind conditions.
    f. Follow the UAV as you fly it, ensuring through the viewer on your phone that the scene is being smoothly captured.
    g. Once you have returned to where you started, land the drone and turn it and the controller off.



11. Return inside to your computer with the SD card after packing away the drone by reversing the steps you took to unpack it. Please charge any dead batteries.
12. Connect your phone to your laptop via USB and open the DJI Go 4 folder in your phone’s file system.
13. Find a folder called FlightLogs, copy the file generated for the date and time you just flew (or any other date/time if you’re revisiting this process).
14. Move the file to your computer into whatever file system you have arranged for this project.
15. Open this website: https://www.phantomhelp.com/logviewer/upload/
    a. Upload your flight log TXT file by doing the captcha and browsing for the file, it may take a minute to load depending on the size
    b. Ensure the flight trajectory looks right based on your expectation of what to find in this file.
    c. Click the export CSV button and wait for the download to finish.
    d. Extract the downloaded file so you have a TXT file you can open.
    e. Open and read the TXT file.

f. Go to column BN and make sure there are three instances of Camera.isVideo switching from False to True (should match the number of videos you took).
g. Close the file.



Download KML | Download CSV | Download Flight Log

Map Size: **Small** | Medium | Large

▶1x ■

Time	Flight Mode	GPS	IMU Altitude	VPS Altitude	Speed	Home Distance	Battery	Battery Voltage	Cell 1	Cell 2	Cell 3	Cell 4	Cell Deviation	Message
0m 0.4s	Starting Motors	14 satellites	0 ft	0.3 ft	0 mph	25.8 ft	77%	16.034 V	4.01 V	4.01 V	4.01 V	4.01 V	0.008 V	Data R
0m 1.6s	Auto Takeoff	14 satellites	0 ft	0.3 ft	0 mph	26.0 ft	77%	15.971 V	3.98 V	3.99 V	4.00 V	4.00 V	0.016 V	Flight
0m 2.4s	Auto Takeoff	14 satellites	0 ft	0.3 ft	0.2 mph	0 ft	77%	15.526 V	3.89 V	3.89 V	3.89 V	3.87 V	0.023 V	Home
0m 3.4s	Auto Takeoff	13 satellites	1.0 ft	2.0 ft	0.4 mph	1.1 ft	77%	15.526 V	3.89 V	3.89 V	3.89 V	3.87 V	0.023 V	

16. Connect and open the SD card's file system on your computer.
17. Move the video files you took to wherever you have your file system for this project set up.
18. In a new terminal, use exiftool to find the metadata timestamps for the start of the videos you took like this:

EXAMPLE:

```
exiftool
/home/desiree/ASRL/Thesis/BuddySystemDatasets/feb19Dome/trainingVids/DJI_0016.MP4
```

19. Look for "Create Date", record that time, and then use an online epoch time converter to obtain the time in epoch time.

```
desiree@Desiree-ThinkPad-P53:~$ exiftool /home/desiree/ASRL/Thesis/BuddySystemDatasets/DomeOrbit2/Trai
ningVids/DJI_0014.MP4
ExifTool Version Number         : 11.88
File Name                       : DJI_0014.MP4
Directory                       : /home/desiree/ASRL/Thesis/BuddySystemDatasets/DomeOrbit2/TrainingVid
s
File Size                       : 1060 MB
File Modification Date/Time     : 2024:10:31 12:29:18-04:00
File Access Date/Time           : 2025:03:10 21:29:39-04:00
File Inode Change Date/Time     : 2024:11:28 14:46:51-05:00
File Permissions                : rw-r--r--
File Type                       : MP4
File Type Extension             : mp4
MIME Type                       : video/mp4
Major Brand                     : MP4 Base w/ AVC ext [ISO 14496-12:2005]
Minor Version                   : 2014.2.0
Compatible Brands               : avc1, isom
Media Data Size                 : 1111473683
Media Data Offset               : 40
Movie Header Version            : 0
Create Date                     : 2024:10:31 16:25:25
Modify Date                     : 2024:10:31 16:25:25
Time Scale                      : 30000
Duration                        : 0:03:42
Preferred Rate                  : 1
Preferred Volume                : 100.00%
```

20. Repeat steps 17 and 18 for every video you recorded so you wind up with the following information:

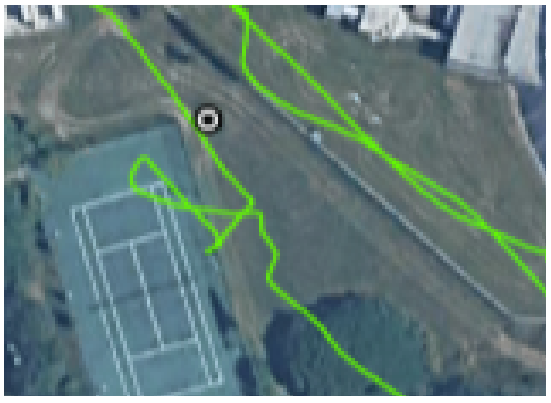
    EXAMPLE:
    Dome w/ spray paint - (num vids matches num true segments)
    DJI_0001: POV, (12.29.31) (12:30:33 = 1738949433000)
    DJI_0002: Straight down (12.36.54) (12:37:42 = 1738949862000)
    DJI_0003: Orbit (12.45.06) (12:45:40= 1738950340000)

21. Now, set up the virtual_teach_vtr_wrapper project from the following repo: https://github.com/desifisker/virtual_teach_vtr_wrapper/tree/main
    a. Follow installation instructions
        i. NOTE: if you already have vtr3 installed - you can skip some steps
    b. Download the example dataset, or setup your own, in the /virtual_teach_vtr_wrapper/data folder

22. From the launch folder in virtual_teach_vtr_wrapper (outside any Docker container), use launch 'ImageExtraction.sh' to process the videos from the drone flight and geo-register the frames

    EXAMPLE:
    ```
    cd ${VTRROOT}/virtual_teach_vtr_wrapper/launch
    chmod +x ImageExtraction.sh ImageProcessor.sh Gazebo.sh TeachMap.sh

    ./ImageExtraction.sh
    "${VTRROOT}/virtual_teach_vtr_wrapper/data/test_press/DJIFlightRecord_2025-02-22_[11-59-34].csv"
    "${VTRROOT}/virtual_teach_vtr_wrapper/data/test_press/DJI_0001-001.MP4"
    "1740243662000" "${VTRROOT}/virtual_teach_vtr_wrapper/data/test_press/images"
    "${VTRROOT}/virtual_teach_vtr_wrapper/data/test_press/all_image_poses.txt" DJI
    ```

23. Now open the /data/images folder with the video frames in it, and go through them all to delete blurry ones, similar/near-duplicates, or instances of prolonged standstill footage that may confuse colmap's SfM. These images may come from repeated parts of the trajectory due to imprecise flying like in this small section:



24. From the launch folder in virtual_teach_vtr_wrapper (outside any Docker container), use launch ‘ImageProcessor.sh’ to filter and scale the geo-registered frames and then run colmap to create inputs for nerfstudio

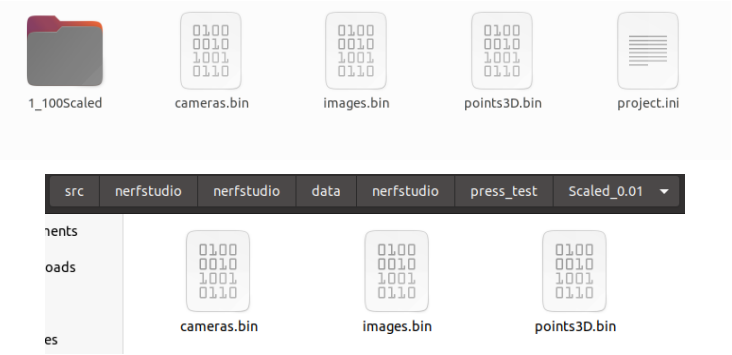
    EXAMPLE:

    ```
    cd ${VTRROOT}/virtual_teach_vtr_wrapper/launch

    ./ImageProcessor.sh "${VTRROOT}/virtual_teach_vtr_wrapper/data/test_press/images"
    "${VTRROOT}/virtual_teach_vtr_wrapper/data/test_press/colmap"
    "${VTRROOT}/virtual_teach_vtr_wrapper/data/test_press/all_image_poses.txt"
    "${VTRROOT}/virtual_teach_vtr_wrapper/data/test_press/colmap/filtered.txt" "0.01"
    "${VTRROOT}/virtual_teach_vtr_wrapper/data/test_press/colmap/database.db"
    "${VTRROOT}/virtual_teach_vtr_wrapper/data/test_press/colmap/Scaled" "press_test"
    ```

Phase 2: NeRF Training

The following steps detail the NeRF training procedure with Nerfstudio. If you have set up VirT&R with the docker image made for the project, all commands should be run in a terminal inside this docker image to work.

1. After running the ‘ImageProcessor.sh’ script, you should have three .bin files (both scaled and unscaled in virtual_teach_vtr_wrapper/data. The scaled folder of .bin files and the folder of images they correspond to should have also been copied to the correct data folder in nerfstudio: (${VTRROOT}/virtual_teach_vtr_wrapper/src/nerfstudio/data/nerfstudio/test_press).

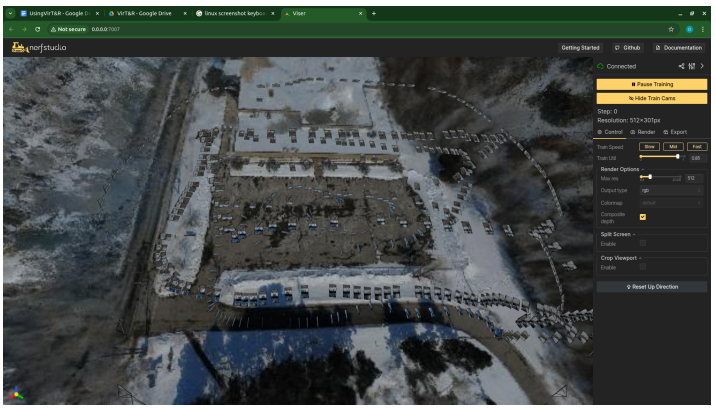


2. Enter the virtr Docker container to use the following command to train a NeRF of the scene (running the previously helper script should already leave you in this location):

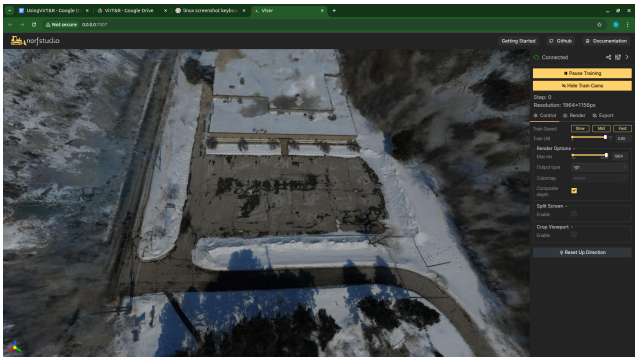
   EXAMPLE:

   ```
   docker exec -it virtr bash
   cd $NERF
   conda activate nerfstudio

   ns-train nerfacto --vis viewer --data data/nerfstudio/press_test
   --viewer.quit-on-train-completion False colmap --colmap_path Scaled_100
   --downscale_factor=1 --orientation_method=none --center_method=none
   --assume_colmap_world_coordinate_convention=False
   ```

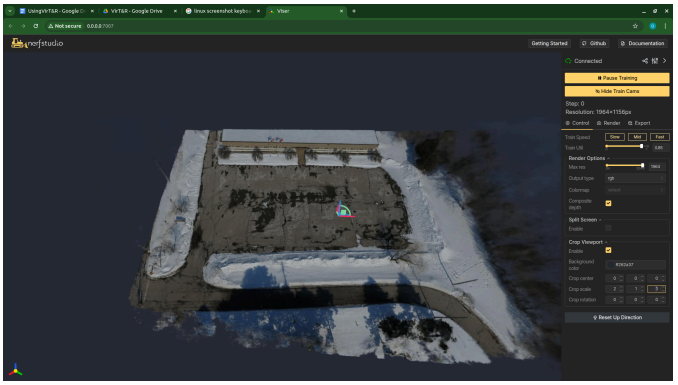
3. Once the NeRF is done training, ctrl+click the HTTP link to open the viewer from the terminal.



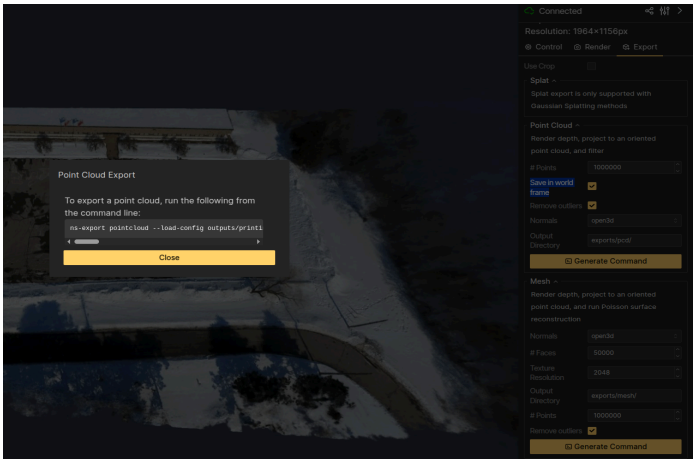
4. Examine the NeRF has trained to a decent quality. (Use the resolution slider bar to increase rendering quality).



5. Crop the scene so only the area the UGV will be driving in is saved using the crop box option on the side panel.
    a. Try to get rid of blurry artifacts in the sky and surroundings by doing this.



6. Go to the exports side panel and generate the commands for exporting the point cloud and mesh, (adjust the number of points and faces in the point cloud and mesh respectively to be an order of magnitude higher than the default - **MAKE SURE TO SAVE POINT CLOUD IN WORLD FRAME**):

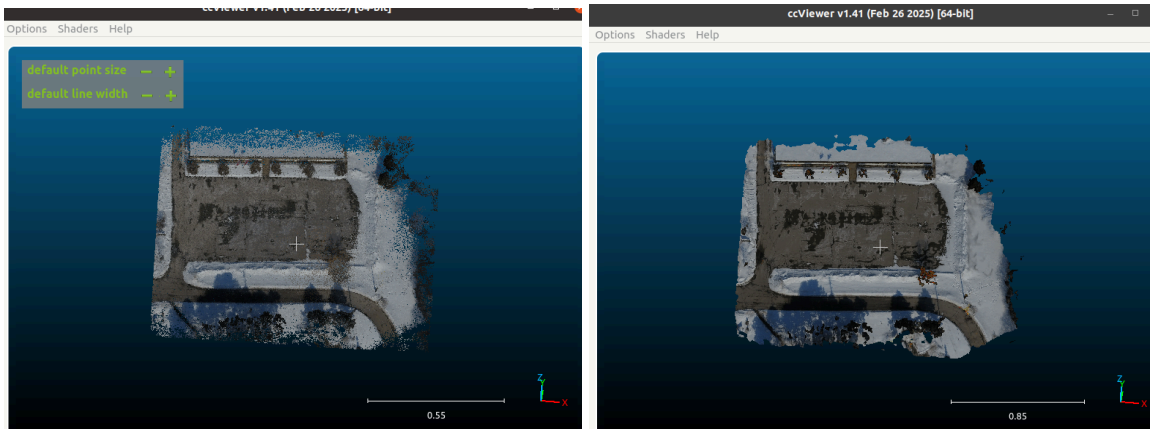


7. Close the viewer and quit training the scene, then in the same terminal, enter the generated commands (they may take up to 15 minutes depending on the scene size):

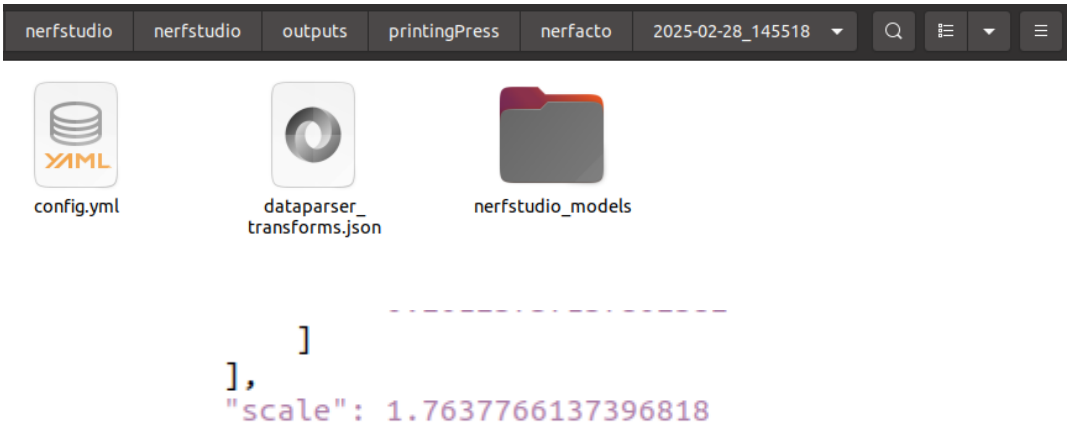
EXAMPLE:

```
ns-export pointcloud --load-config
outputs/feb19Dome/nerfacto/2025-02-19_171352/config.yml --output-dir exports/pcd/
--num-points 1000000 --remove-outliers True --normal-method open3d
--save-world-frame True --obb_center 0.3997362713 0.1145217735 -0.0983033677
--obb_rotation 0.8704366783 -0.0422337007 0.2335225570 --obb_scale 1.2000000477
1.0000000000 0.4000000060

ns-export poisson --load-config
outputs/feb19Dome/nerfacto/2025-02-19_171352/config.yml --output-dir exports/mesh/
--target-num-faces 50000 --num-pixels-per-side 4096 --num-points 1000000
--remove-outliers True --normal-method open3d --obb_center 0.3997362713
0.1145217735 -0.0983033677 --obb_rotation 0.8704366783 -0.0422337007 0.2335225570
--obb_scale 1.2000000477 1.0000000000 0.4000000060
```

8. Now, open the resulting files $NERF/exports, to verify they are as expected.



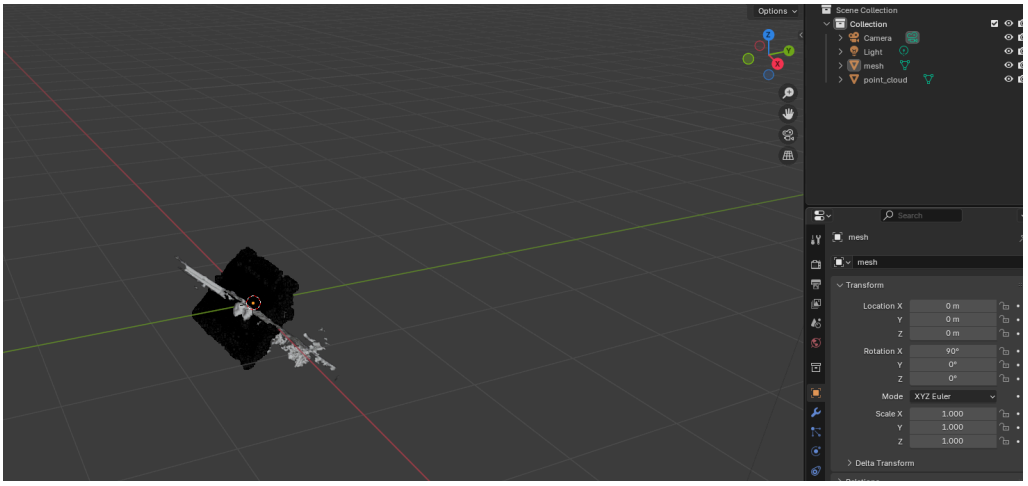
9. Go to $NERF/outputs/test_press/{date_time}/data_parser.json and look for “scale:” at the bottom (the number will be different, but record it for later).



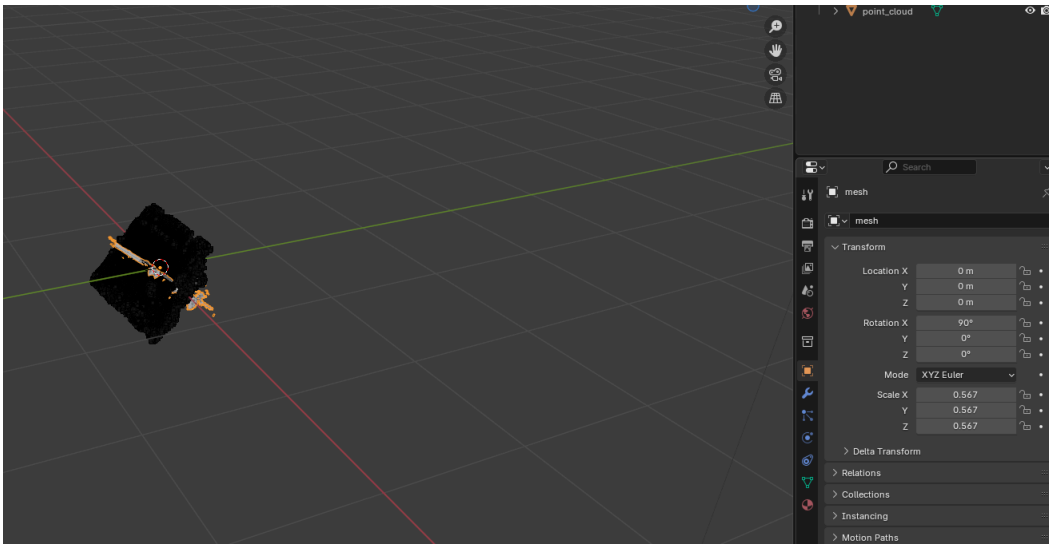
Phase 3: PointCloud and Path Association

This section can be further segmented into actions to prepare and use the NeRF Mesh and actions to prepare and use the NeRF Point cloud. Both parts involve using Blender, but the Mesh process involves gazebo and some custom scripts, whereas the PointCloud is used in some custom scripts and then given right to VirT&R.

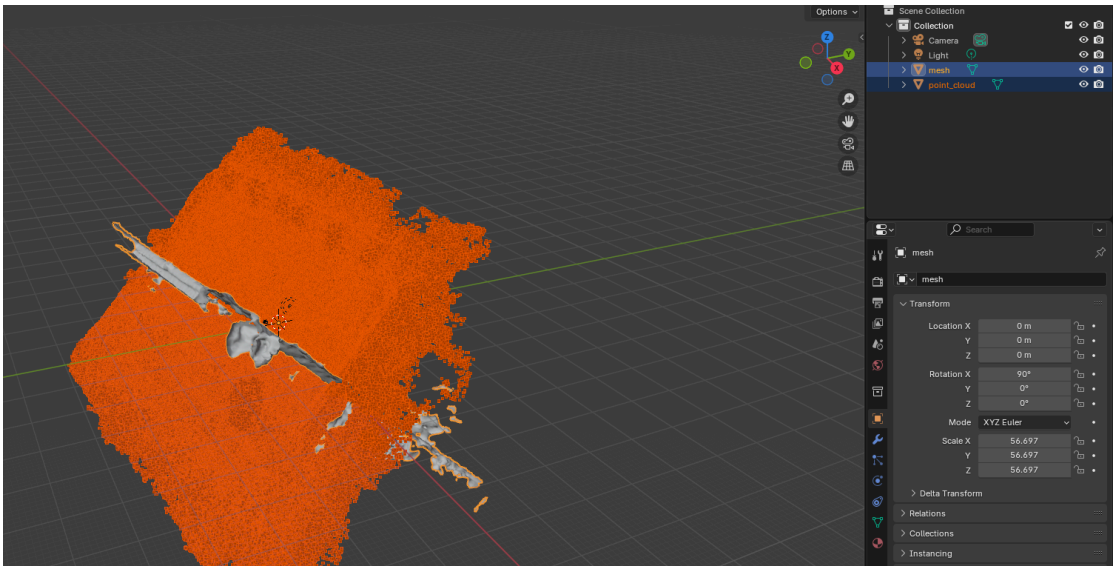
1. Now that the mesh and point cloud have been generated, they need to be taken from $NERF/exports/Mesh/test-press/ and $NERF/exports/Pointclouds/test-press/ to the virtual_teach_vtr_wrapper/data/meshes and virtual_teach_vtr_wrapper/data/pointclouds folders respectively (make sure to grab all files produced).
2. Ensure you're still in the virtr Docker container and open Blender to a blank project then import the .obj file and .ply files.



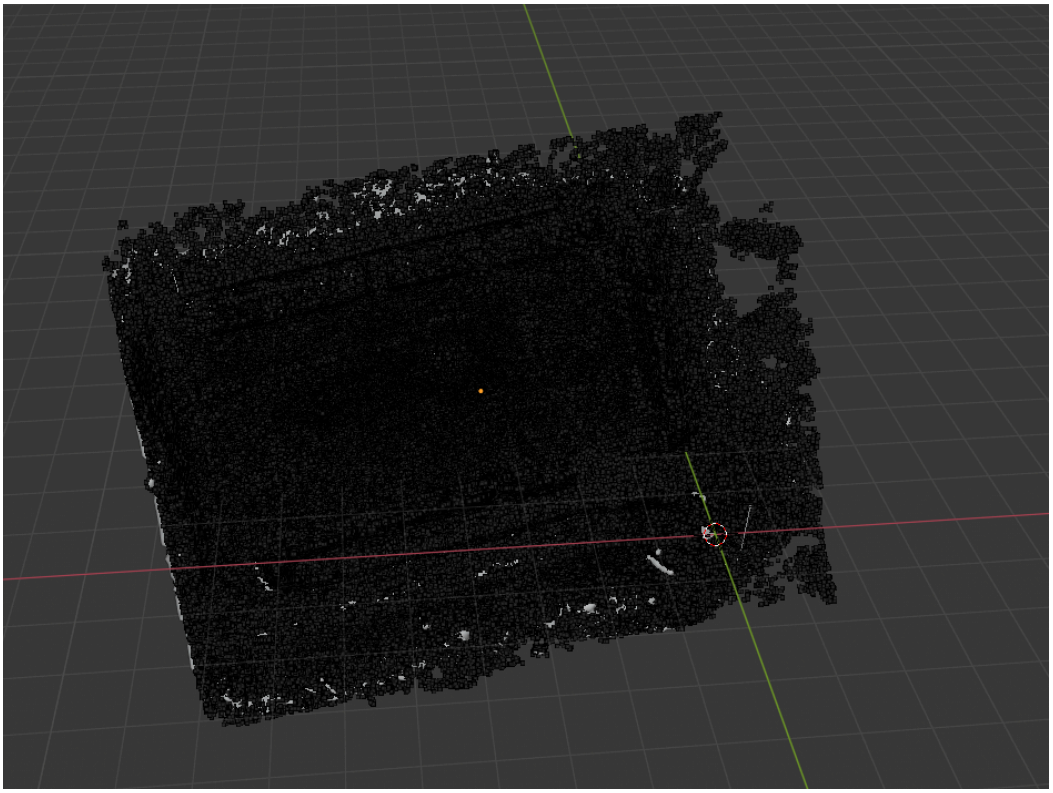
3. Scale up the mesh by the previously saved number from the data_parser.json by using the x,y,z scale toggles on the right side panel.



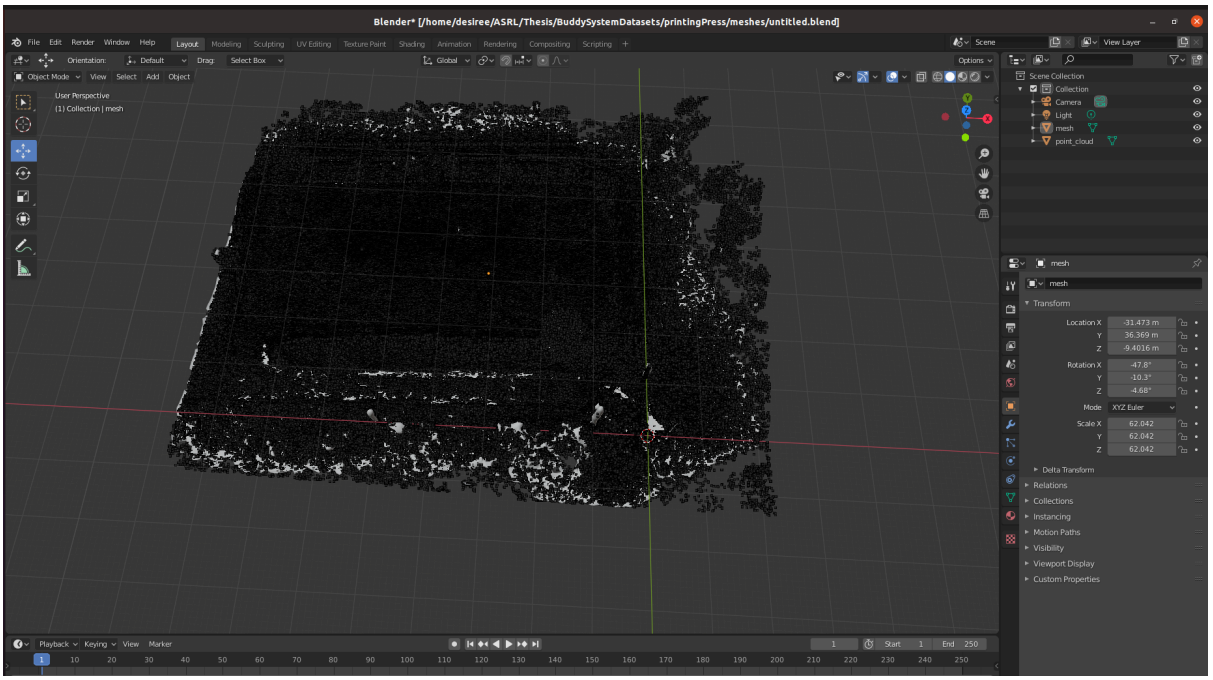
4. Then shift+click on both the mesh and point cloud, press S, and type in the number intentionally used for downscaling with Colmap (100 in the example case).



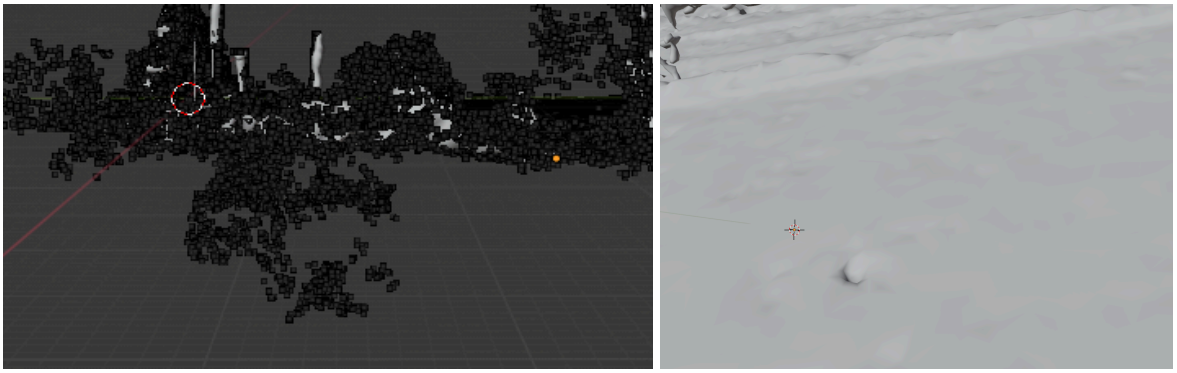
5. The mesh usually loads in 90 degrees rotated from the point cloud, so this can be undone as well. Now the mesh and point cloud should be perfectly aligned.



6. Rotate them both together so the blender origin is where the gazebo world origin should be (where the UGV will spawn) slightly above the ground.



7. Crop and clean both the mesh and the point cloud to remove odd artifacts.
    a. You may need to smooth the mesh out a bit by going to edit mode, selecting vertices, right clicking, and using the smooth feature, don't do this too much as it blurs the ground.



8. Save the mesh as a .dae file, and save the point cloud and a .ply file using the File>Export function in the top left corner (**MAKE SURE TO SAVE THE SELECTIONS ONLY, AND INCLUDE SAVING NORMALS WITH THE POINT CLOUD**).

Process for Gazebo Sim:

1. From the launch folder in virtual_teach_vtr_wrapper (outside any Docker container), use launch ‘Gazebo.sh’ to prepare the gazebo simulation.

   EXAMPLE:

   ```
   cd ${VTRROOT}/virtual_teach_vtr_wrapper/launch

   ./Gazebo.sh "${VTRROOT}/virtual_teach_vtr_wrapper/data/test_press/meshes/mesh.dae"
   "${VTRROOT}/virtual_teach_vtr_wrapper/data/test_press/meshes/material_0.png"
   "test_press_world"
   ```

2. Then enter the virtr Docker container to launch Gazebo and begin the teleoperation (3 terminals in the container will be needed).

   EXAMPLE:

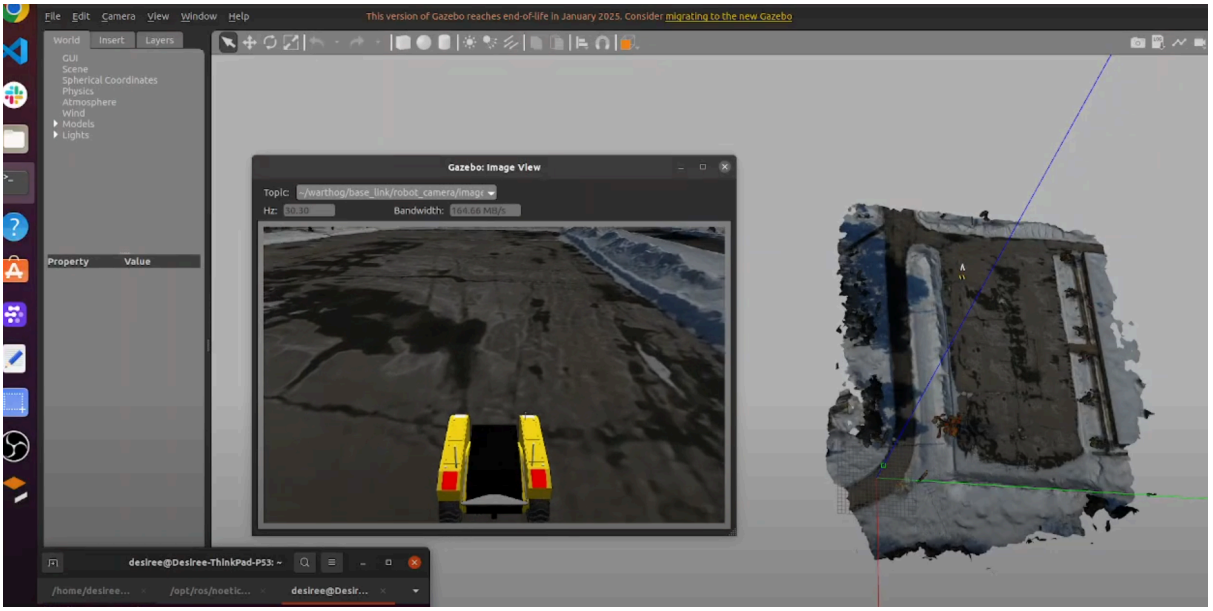
   ```
   docker exec -it virtr bash
   conda deactivate
   source /opt/ros/noetic/setup.bash
   source ~/ASRL/vtr3/virtual_teach_vtr_wrapper/catkin_ws/devel/setup.bash

   roslaunch warthog_gazebo test_press_world.launch
   ```

3. Then in one of the new terminal windows (also in the virtr docker container), use the following command to set up keyboard or joystick control:

   EXAMPLE:

   ```
   roslaunch teleop_twist_joy teleop.launch
   ```

4. To open the second window of the warthog’s POV camera, access and open the window by going to the top left and finding it here: Window>Topic Visualization> /warthog/base_link/robot_camera/image



5. Lastly, steer the warthog to the place you want to begin the path using the joystick and the run the following command to record the path in the final new virtr docker container terminal:

   EXAMPLE:

   ```
   rosrun warthog_gazebo_path_publisher save_path.py
   ```

6. The path saved in a txt file from this will be given to the virT&R package later.

Process for Associating Point Cloud Submaps:

1. From the launch folder in virtual_teach_vtr_wrapper (outside any Docker container), use launch ‘TeachMap.sh’ to prepare and run vtr_virtualteach package. Note: it is supposed to say ‘Failed to find match for field curvature’ during the creation of the map because we are not supplying that data - no problemo!

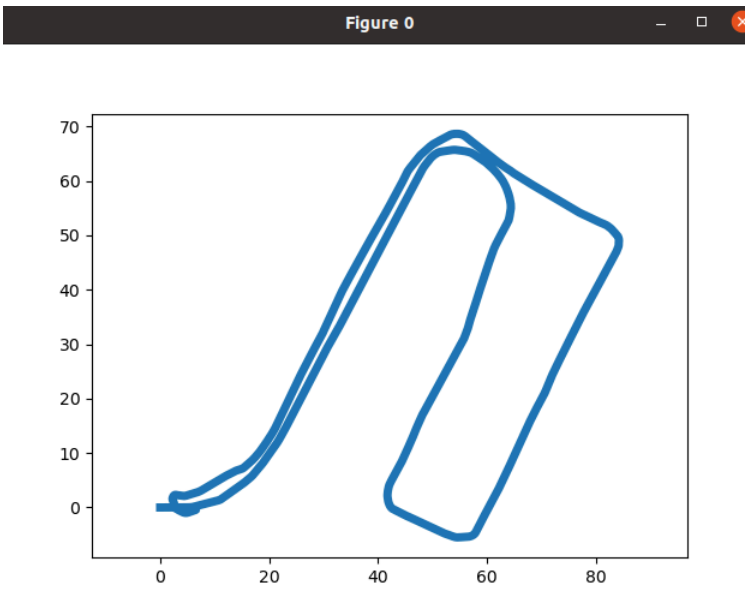
   EXAMPLE:

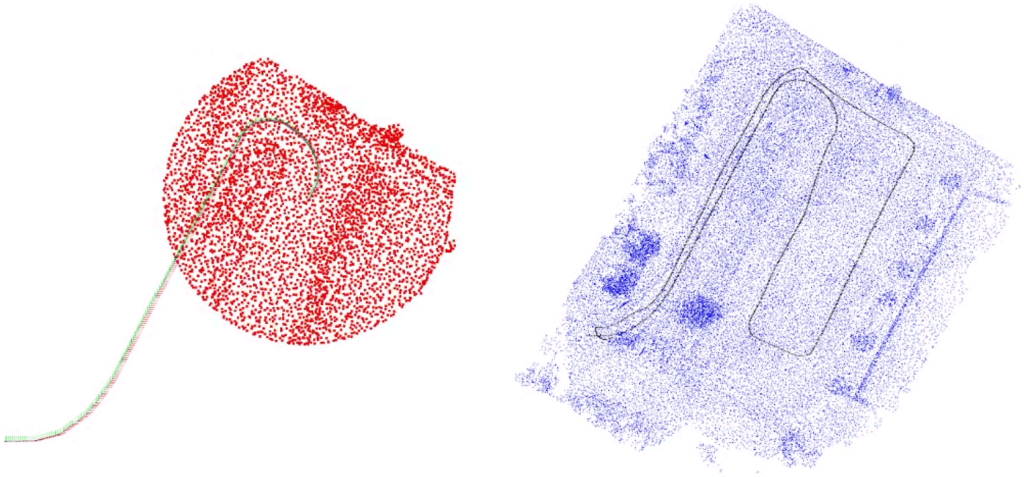
   ```
   cd ${VTRROOT}/virtual_teach_vtr_wrapper/launch

   ./TeachMap.sh
   "${VTRROOT}/virtual_teach_vtr_wrapper/data/test_press/pointclouds/point_cloud.ply"
   "${VTRROOT}/virtual_teach_vtr_wrapper/data/test_press/paths/relative_transforms.csv
   " "test_press"
   ```

2. Now a pose graph has been generated for the path driven through the mesh. Before using it online with LT&R it should be checked using the python tools to ensure the route is as expected. Type the following commands to show what the teach path looks like and then to plot the submaps along the teach path (red point clouds are at the vertex, blue point clouds are being pointed to from the vertex):

   EXAMPLE:

   ```
   docker exec -it vtr3 bash

   source ${VTRSRC}/main/install/setup.bash
   source /opt/ros/humble/setup.bash

   cd ${VTRROOT}/vtr3_posegraph_tools/vtr3_pose_graph

   python3 samples/plot_teach_path.py -g
   /home/desiree/ASRL/vtr3/data/ExistingGraph/pose_graph

   python3 src/vtr_odom_extractor/plot_submaps.py -g
   /home/desiree/ASRL/vtr3/data/nerf_with_odom_path/graph
   ```





Once the virtually-generated pose graph has been made using the path driven on the mesh from gazebo and the point cloud from the NeRF model, and it has been verified to follow the expected route with the pose graph tools, it can be loaded into the ${VTRROOT}/temp>{project_name} folder to be used online on the Warthog with LT&R just as normal pose graphs are. This is the part of the pipeline that remains unchanged as it is only the process for making the teach map that is altered here.