(Open-source) Photogrammetry on HPC clusters

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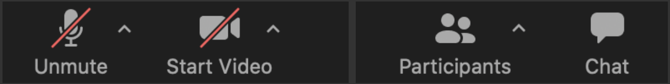
Zoom controls

- Please mute your microphone and camera unless you have a question
- To ask questions at any time, type in Chat, or Unmute to ask via audio
  - please address chat questions to "Everyone" (not direct chat!)
- Raise your hand in Participants



- Email training@westdri.ca
- Our winter/spring training schedule `https://bit.ly/wg2024a`
  - webinars, courses, summer school at SFU on May 27–31

Oxford English Dictionary: PHOTOGRAMMETRY, n.
The technique of using photographs to ascertain measurements of what is photographed, esp. in surveying and mapping.

Nowadays, photogrammetry almost exclusively refers to the process of constructing a 3D model (= geometry of a scene) by analyzing a unordered series of photographs / videos of the same subject captured from various angles and/or with different lighting conditions

In a sense, it's the opposite of photography (which does 3D $\rightarrow$ 2D):
now recover depth information from 2D images

Proprietary photogrammetry software

- Metashape (Mac/Windows/Linux)
  - from Agisoft
  - educational discount
  - Linux version can run on HPC clusters, uses node-locked licenses
  - seems to be a popular choice in the academia
- RealityCapture: cloud or deskop (Windows only), expensive
- ReCap Photo from Autodesk
- etc.

Our approach

- Only open source
- Photogrammetry is very computationally intensive ⇒ if part of research, it is a natural application to run on HPC clusters in batch mode
  - ⇒ all command line, no GUI
  - ⇒ looking for plug and play functionality: in go images, out comes a 3D textured model
    - don't want to adjust parameters or fiddle with intermediate results
- Zero personal experience with command-line photogrammetry before this webinar
- For many of these packages, the official documentation and tutorials focus on working via a GUI ⇒ discovering actual shell commands and parameters requires digging well beyond documentation
- Do not want to compile long software dependencies and deal with complicated and obscure instructions ⇒ relying on Docker Hub containers

Creating container images on a cluster

In simpler cases you might be able to pull from Docker Hub directly on a cluster, e.g. on Cedar with online access from compute nodes:

```
cd ~/scratch
module load StdEnv/2023 apptainer/1.2.4
salloc --cpus-per-task=1 --time=0:60:0 --mem-per-cpu=3600 --account=...
mkdir $SLURM_TMPDIR/{tmp,cache}    # to avoid Lustre filesystem limitations on the host
export APPTAINER_TMPDIR=${SLURM_TMPDIR}/tmp
export APPTAINER_CACHEDIR=${SLURM_TMPDIR}/cache    # replaces `$HOME/.apptainer/cache`
apptainer pull docker://geointeractive/opensfm     # 371M file opensfm_latest.sif
apptainer pull docker://opendronemap/odm           # 540M file odm_latest.sif
apptainer pull docker://threedscan/meshroom        # create 533M file meshroom_latest.sif
cp odm_latest.sif ~/scratch/<pipeline>             # especially if in $SLURM_TMPDIR
```

... however – especially for larger images – you might run into problems, e.g. with:

- permissions for files inside the container
- Internet access from a compute node

Creating container images in a cloud VM

For larger container images you are more likely to run into problems, e.g. with permissions, Lustre filesystem limitations, Internet access from a compute node

⇒ create them as root on a Linux machine, if you have one

- you can do this inside a VM in our cloud - bash commands in the next slide
  1. (if you don't have one) apply for a cloud project – could be on Arbutus, Béluga, Graham, or Cedar
  2. inside that project, create an instance, associate a external floating IP
  3. create a volume (50GB should be sufficient) and attach it to your instance
  4. format and mount the volume in your VM
  5. install Apptainer
  6. `apptainer pull <image>.sif docker://...` into your 50GB mount

Creating container images in a cloud VM (cont.)

Example for an Ubuntu VM in Arbutus OpenStack cloud:

```
ls /dev/disk/by-id                  # get the attached disk's ID and use it in the next line
device=/dev/disk/by-id/virtio-...
sudo mkfs.ext4 $device              # format the volume
sudo mkdir -p /data                 # create a mount point
sudo mount $device /data            # mount the volume
sudo chmod og+rwX /data             # give write access to non-root

sudo apt update
sudo apt install -y software-properties-common
sudo add-apt-repository -y ppa:apptainer/ppa
sudo apt update
sudo apt install -y apptainer

export APPTAINER_TMPDIR=/data/tmp
export APPTAINER_CACHEDIR=/data/cache   # replaces default `$HOME/.apptainer/cache`
cd /data && mkdir -p tmp cache
apptainer pull docker://alicevision/meshroom:2023.3.0-av3.2.0-centos7-cuda11.3.1
scp meshroom_*.sif <username>@<cluster>.alliancecan.ca:scratch/meshroom
```

Image acquisition

- Avoid smooth surfaces and reflections: these make it much harder to reconstruct a 3D model
- Many small details make it easier to find match points, i.e.
  - OpenSfM's tutorial `https://opensfm.org/docs/using.html` demos creating an accurate 3D point cloud from only three photographs (Berlin): many intricate details
  - having a unique shape helps, as the edges will add match points
- Take 60-70 images for a detailed reconstruction
- However, more photographs $\Rightarrow$ slower processing
- Try to crop the background, if it is not related to the main object
- Important to have all pictures in-focus

84 input files

High-level pipeline view

1. Structure-from-Motion (SfM), aka sparse reconstruction
   - infer the 3D scene structure: figuring common points in 2D overlapping images, reconstructing their 3D positions along with camera poses (camera positions and orientations)

   ⇒ output is a set of calibrated cameras with a sparse point cloud

2. MultiView-Stereo (MVS), aka dense reconstruction
   - generate a dense geometric surface using the calibrated cameras + the sparse point cloud from the previous step

   ⇒ output is a textured mesh, in OBJ file format with the corresponding MTL and texture files

   2.1 dense point-cloud reconstruction (densification)
   2.2 mesh reconstruction (meshing)
   2.3 mesh refinement
   2.4 mesh texturing

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In practice, each of these in turn contains multiple steps that depend on the specific software chain

Structure-from-Motion (SfM)

OpenSfM package `https://opensfm.org`

- Open-source SfM library to build 3D models from images, written in Python
- Documentation `https://opensfm.org/docs`
- Source code `https://github.com/mapillary/OpenSfM`
- In addition to input images, you can also supply:
  1. `gcp_list.txt` lists Ground Control Points to help you scale+orient your 3D model
  2. `config.yaml` with additional parameters to overwrite the defaults, e.g.

```
processes: 8                     # number of threads to use
depthmap_min_consistent_views: 2 # min number of views that should reconstruct a valid point
                                 # (default 3; smaller number will give you more points)
depthmap_save_debug_files: yes   # save debug files with partial reconstruction results
feature_process_size: 1024       # photo dimensions for feature extraction
```

- A discussion of most important OpenSfM parameters in `https://github.com/OpenDroneMap/ODM/issues/769`

Running OpenSfM on a cluster

```
#!/bin/bash
#SBATCH --cpus-per-task=1
#SBATCH --time=3:0:0    # on Cedar took 2h23m for this problem on one CPU core
#SBATCH --mem-per-cpu=3600
#SBATCH --account=...
module load StdEnv/2023 apptainer/1.2.4
# run the entire OpenSfM pipeline, ~1h40m on one CPU core
find vase -mindepth 1 -maxdepth 1 -not -name 'images' | xargs /bin/rm -rf
apptainer exec -C --pwd $(pwd -P) opensfm_latest.sif /source/OpenSfM/bin/opensfm_run_all vase
```

```
cd ~/scratch/opensfm
>>> upload input images to ./vase/images
sbatch submit.sh
...
find vase -name "*.ply" 2>/dev/null
```

Underneath, this runs:

```
/source/OpenSfM/bin/opensfm extract_metadata vase
/source/OpenSfM/bin/opensfm detect_features vase
/source/OpenSfM/bin/opensfm match_features vase
/source/OpenSfM/bin/opensfm create_tracks vase
/source/OpenSfM/bin/opensfm reconstruct vase
/source/OpenSfM/bin/opensfm mesh vase
/source/OpenSfM/bin/opensfm undistort vase
/source/OpenSfM/bin/opensfm compute_depthmaps vase
```

Download to your computer:

```
scp cedar:scratch/opensfm/vase/depthmaps/merged.ply .
```

Demo OpenSfM on a training cluster for BERLIN dataset

Three input images ⇒ this takes only few mins:

```
cd ~/scratch/opensfm
module load StdEnv/2023 apptainer/1.2.4
salloc --cpus-per-task=1 --time=0:30:0 --mem-per-cpu=3600
/bin/rm -rf berlin
apptainer shell opensfm_latest.sif
cp -r /source/OpenSfM/data/berlin .    # must be on a writable filesystem, to store results
/source/OpenSfM/bin/opensfm_run_all berlin   # run the entire OpenSfM pipeline
...
find berlin -name "*.ply" 2>/dev/null | xargs ls -lh
```

Larger VASE run

Let's check out results in `~/tmp/photogrammetry/opensfm/vase`

Only a point cloud – no mesh or texture

MultiView-Stereo (MVS), aka dense reconstruction

A popular package for this is OpenMVS `https://cdcseacave.github.io`

- Open-source library to reconstruct everything from dense point clouds to textured meshes
- Somewhat sparse documentation `https://github.com/cdcseacave/openMVS/wiki`
- Source code `https://github.com/cdcseacave/openMVS`
- Instead of running it separately, let me show a pipeline built on top of it

OpenDroneMap, aka ODM

Details at https://www.opendronemap.org

- Open-source toolkit for processing aerial imagery
- Skip its georeferencing step to use it for regular photogrammetry
- Built on top of OpenSfM and OpenMVS
- Good description of the entire project
  `https://hub.docker.com/r/opendronemap/odm`

Testing OpenDroneMap on the training cluster with `salloc`

```
cd ~/scratch/odm
>>> upload input images to ./vase/images/

module load StdEnv/2023 apptainer/1.2.4
salloc --cpus-per-task=8 --time=0:120:0 --mem-per-cpu=1200
/bin/rm -rf vase/{benchmark.txt,*.json,*.txt,opensfm}
/bin/rm -rf vase/odm_{dem,filterpoints,meshing,orthophoto,report}
/bin/rm -rf vase/odm_{texturing,texturing_25d,georeferencing}
apptainer shell odm_latest.sif
python3 /code/run.py --end-with mvs_texturing $(pwd)/vase
```

Underneath, `run.py` *without flags* will attempt to run the following steps:

1. `dataset`
2. `split`
3. `merge`
4. `opensfm` - open-source Structure from Motion
5. `openmvs` - Multi-View Stereo reconstruction
6. `odm_filterpoints`
7. `odm_meshing`
8. `mvs_texturing`
9. `odm_georeferencing` - map to geographic coordinates
10. `odm_dem` - digital surface+terrain (elevation?) model
11. `odm_orthophoto` - geometrically-corrected image of the ground (high-resolution map from aerial mapping)
12. `odm_report`
13. `odm_postprocess`

Production OpenDroneMap runs on a cluster

```
#!/bin/bash
#SBATCH --cpus-per-task=16
#SBATCH --time=2:0:0
#SBATCH --mem-per-cpu=3600
#SBATCH --account=...
module load StdEnv/2023 apptainer/1.2.4
/bin/rm -rf vase/{benchmark.txt,*.json,*.txt,opensfm}
/bin/rm -rf vase/odm_{dem,filterpoints,meshing,orthophoto,report,\
                      texturing,texturing_25d,georeferencing}
apptainer exec odm_latest.sif python3 /code/run.py --end-with mvs_texturing $(pwd)/vase
```

```
cd ~/scratch/odm
upload input images to ./vase/images/
sbatch submit.sh
```

```
srun --jobid=... --pty bash
htop -u $USER -s PERCENT_CPU
```

Fine-grained control in OpenDroneMap

For more control, take a look at the output file from your job, and there you will see the exact commands with parameters, e.g.

```
$ grep running slurm-<jobID>.out
...
[INFO]    running renderdem "/scratch/razoumov/odm/vase/odm_filterpoints/point_cloud.ply"
  --outdir "/scratch/razoumov/odm/vase/odm_meshing/tmp" --output-type max
  --radiuses 0.031415926535897934,0.044428829381583667,0.06283185307179588
  --resolution 0.02 --max-tiles 0 --decimation 1 --classification -1
  --tile-size 4096 --force
...
```

Postprocessing

Download to your computer:

```
cd ~/tmp/photogrammetry/odm/vase

f1=odm_filterpoints/point_cloud.ply                    # preliminary point cloud
f2=opensfm/undistorted/openmvs/scene_dense.ply         # dense point cloud
f3=odm_meshing/odm_mesh.ply                            # polygonal mesh
f4=odm_texturing/odm_textured_model_geo.obj            # textured mesh (pointing to materials)
f5=odm_texturing/odm_textured_model_geo.mtl            # and its texture
                                     # (material definitions pointing to PNGs)
f6=odm_texturing/"odm_textured_model_geo_material*.png"    # material PNGs

scp cedar:/scratch/razoumov/odm/vase/{$f1,$f2,$f3,$f4,$f5,$f6} .
```

Let's check out results in `~/tmp/photogrammetry/odm/vase`

- open `*.ply` point clouds using ParaView's PDAL reader
- open `*.ply` meshes using ParaView's PLY reader
- open `odm_textured_model_geo.obj` in Meshlab (next slide)

Postprocessing in Meshlab

1. `cp odm_textured_model_geo.obj clip.obj`
2. Open `clip.obj` in Meshlab
3. In the toolbar: Select Vertices, Delete Selected Vertices, CMD-backspace
4. File | Export Mesh... (will be written back to clip.obj)
5. To pan: CMD-mouse

While you can load an OBJ file into ParaView, it lets you apply only one texture per polygonal mesh. Since ODM returns a single mesh with many textures, displaying it in ParaView would require splitting the original mesh into a set of meshes (and applying a separate texture to each) – possible but quite labour-intensive.

Meshroom

- Open-source 3D Reconstruction Software `https://alicevision.org/#meshroom` `https://github.com/alicevision/meshroom`
- Supported by the AliceVision Association, a non-profit organization whose goal is to democratize 3D digitization technologies from photographs
- Built on top of OpenSfM
- An NVIDIA CUDA-enabled GPU is recommended
  - without a supported NVIDIA GPU, only "Draft Meshing" from SfM step can be used for dense 3D reconstruction (very poor quality)
  - only one of 12 steps uses GPU

Meshroom on Docker Hub

- Search for Meshroom on Docker Hub `https://hub.docker.com/search?q=meshroom`
- Official recent versions are problematic:
  - checked alicevision/meshroom:2023.3.0-av3.2.0-centos7-cuda11.3.1 and alicevision/meshroom:2023.2.0-av3.1.0-centos7-cuda11.3.1
  - dense scene reconstruction (DepthMap step) crashes with

```
Assertion `row >= 0 && row < rows() && col >= 0 && col < cols()' failed
```

    - seems like the binary was compiled with debug turned on ... can't use them as is in Apptainer
- Instead, I am using an older version `docker://threedscan/meshroom`
  - compact 533M SIF file; official versions are 4.2GB and larger
  - `meshroom_photogrammetry`, has since been renamed to `meshroom_batch`
  - great experience overall!

Running the entire pipeline in a single step

- Running on a cluster's CPU partition, you will get "No CUDA-Enabled GPU" and the code will stop ⇒ need to submit a GPU job
  - there is a way to override this, but I don't recommend it, as results will be very poor

```
#!/bin/bash
#SBATCH --cpus-per-task=8 --time=1:0:0 --mem-per-cpu=3600 --gpus-per-node=1 --account=...
module load StdEnv/2023 apptainer/1.2.4
cat << EOF > run.py
nvidia-smi
export LC_ALL=C   # for some reason the executable requires localization settings
mkdir -p results && /bin/rm -rf results/*
meshroom_photogrammetry --input vase/images/ --output results
EOF
chmod u+x run.py
apptainer exec --nv meshroom_latest.sif ./run.py
tar cvfz results.tar.gz results $(find /tmp/MeshroomCache/ -name "*log" -o -name "status")
```

```
cd ~/scratch/meshroom
>>> upload input images to ./vase/images/
sbatch submit.sh
```

```
srun --jobid=... --pty bash
htop -u $USER -s PERCENT_CPU
watch -n 3 nvidia-smi   # during step 7 (DepthMap)
```

```
scp cedar:scratch/meshroom/results.tar.gz .
```

Timing

All wallclock times

1	CameraInit	0.123s
2	FeatureExtraction	56s
3	ImageMatching	0.068s
4	FeatureMatching	25s
5	StructureFromMotion	594s
6	PrepareDenseScene	6.5s
7	DepthMap (requires CUDA)	688s
8	DepthMapFilter	189s
9	Meshing	290s
10	MeshFiltering	3.5s
11	Texturing	100s
12	Publish	59s
	Total	33.5m

Look for “elapsedTime” and “Task done” in the logs.

Problem: only 1/3 of the wallclock time was spent on the GPU ...

Splitting the entire pipeline into three steps: step 1

1. Split the workflow into three steps: CPU only + GPU part + CPU only
2. Move output from `/tmp/MeshroomCache` to `./tmp/MeshroomCache`

```
#!/bin/bash
#SBATCH --cpus-per-task=16 --time=0:30:0 --mem-per-cpu=3600 --account=...
module load StdEnv/2023 apptainer/1.2.4
cat << EOF > run.py
export LC_ALL=C
export details="--input vase/images/ --output results --cache $(pwd)/tmp/MeshroomCache"
mkdir -p results && /bin/rm -rf results/*
meshroom_photogrammetry ${details} --toNode CameraInit
meshroom_photogrammetry ${details} --toNode FeatureExtraction
meshroom_photogrammetry ${details} --toNode ImageMatching
meshroom_photogrammetry ${details} --toNode FeatureMatching
meshroom_photogrammetry ${details} --toNode StructureFromMotion
meshroom_photogrammetry ${details} --toNode PrepareDenseScene
EOF
chmod u+x run.py
apptainer exec --nv meshroom_latest.sif ./run.py
```

Splitting the entire pipeline into three steps: step 2

```
#!/bin/bash
#SBATCH --cpus-per-task=8 --time=0:30:0 --mem-per-cpu=3600 --gpus-per-node=1 --account=...
module load StdEnv/2023 apptainer/1.2.4
cat << EOF > run.py
nvidia-smi
export LC_ALL=C
export details="--input vase/images/ --output results --cache $(pwd)/tmp/MeshroomCache"
meshroom_photogrammetry ${details} --toNode DepthMap_1   # requires CUDA
EOF
chmod u+x run.py
apptainer exec --nv meshroom_latest.sif ./run.py
```

Splitting the entire pipeline into three steps: step 3

```
#!/bin/bash
#SBATCH --cpus-per-task=16 --time=0:30:0 --mem-per-cpu=3600 --account=...
module load StdEnv/2023 apptainer/1.2.4
cat << EOF > run.py
export LC_ALL=C
export details="--input vase/images/ --output results --cache $(pwd)/tmp/MeshroomCache"
meshroom_photogrammetry ${details} --toNode DepthMapFilter
meshroom_photogrammetry ${details} --toNode Meshing
meshroom_photogrammetry ${details} --toNode MeshFiltering
meshroom_photogrammetry ${details} --toNode Texturing
meshroom_photogrammetry ${details} --toNode Publish
EOF
chmod u+x run.py
apptainer exec --nv meshroom_latest.sif ./run.py
tar cvfz results.tar.gz results $(find tmp/MeshroomCache/ -name "*log" -o -name "status")
```

Fine-grained control in Meshroom

- For more control, check out a contributed pipeline
  `https://github.com/davidmoncas/meshroom_CLI`
- They replace individual steps with direct calls to `aliceVision/` commands with many flags each, and breaking many individual steps into further sub-steps, e.g.

```
meshroom_photogrammetry --input vase/images/ --output results \
                        --cache $(pwd)/tmp/MeshroomCache --toNode CameraInit
```

becomes

```
mkdir -p 1_CameraInit
/opt/Meshroom-2019.2.0/aliceVision/bin/aliceVision_cameraInit \
    --imageFolder "vase/images/" \
    --sensorDatabase "/opt/Meshroom-2019.2.0/aliceVision/share/aliceVision/cameraSensors.db" \
    --output "1_CameraInit/cameraInit.sfm" --defaultFieldOfView 45 \
    --allowSingleView 1 --verboseLevel "error"
```

Let's check out results in `~/tmp/photogrammetry/meshroom/vase`

Summary

- In production runs, replace `salloc` with `sbatch` and write Slurm submission scripts
- For many of these packages, the official documentation and tutorials focus on working via a GUI, and discovering actual shell commands and parameters requires digging well beyond documentation
- Hopefully, this presentation fills in that gap if you want to run these tools via command line on a cluster
- Other open-source projects to check: COLMAP, MicMac, MVE, OpenMVG, VisualSFM, Regard3D (played with it few years ago in the GUI)
- Free and commercial photogrammetry software review (updated for 2021)

Questions?