3D-Space Mapping via UAV-based RF sensing

Project Readiness Presentation

12/08/2020

Team 4

Customer Mentor/Technical Manager:
Dr. Honggang Zhang

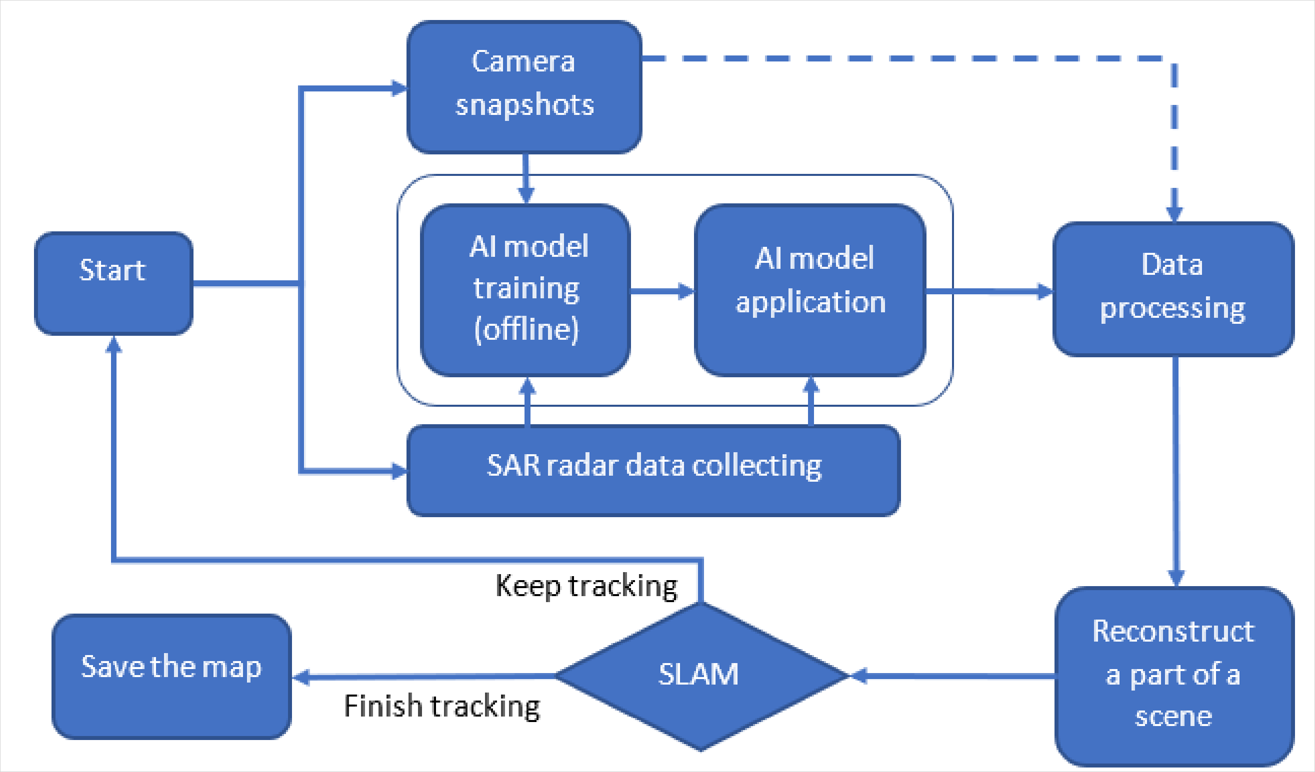
Zhuoming Huang
Alinson Sanquintin (Junior)

Team Roles

- SAR Experiment team:
  - Zhuoming Huang
    - SAR experiments, synthesize radar data for model training
  - Alinson Sanquintin
    - Assist with experiments and data processing in MATLAB, reviewing.
- Neural Network team (external):
  - Yue Sun and Lucas Lomba
    - Building Neural Network to train AI models and generate high-resolution images/depth images.

Initial Design

- Use 64x8 virtual antennas to form a SAR (Synthetic-aperture Radar) structure, collect raw mmWave radar data, and generate raw intensity images
- Use depth images from a 3D camera as ground truth to train neural network models
- The neural network generates high-resolution intensity images or depth images from low-resolution raw images



Design Improvement

- Use 2 sliders to form a SAR (Synthetic-aperture Radar) structure
  - In addition to 64 vertical positions with 8 virtual antennas in horizontal direction, move the radar sensor horizontally as well to improve the azimuth resolution.
  - Virtual antennas: 64x8 -> 64x24
    - -> 64x64 (need more time)
  - Azimuth resolution: 15° -> 5°
- Use CAD models to synthesize radar data and intensity images to train a deep neural network model.
  - We need huge number of data samples (>= 3000) for neutral network training. But it needs significant time to construct a 64x24 SAR in real experiments (at least 1 hour).
  - Speed up data sample collection
  - Less than 1 minute for synthesizing one data sample
    - (not including time for generating CAD models)
  - 3000 samples: 3000hrs -> 50hrs

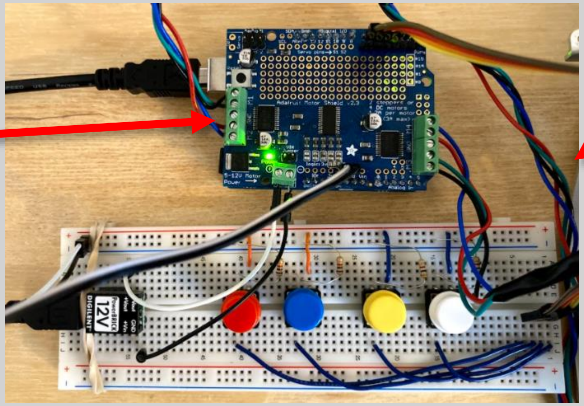
Parts, Tool, Equipment, and Software Availability

- TI IWR6843ISK mmWave radar sensor & Data capture card DCA1000EVM
  - Collect raw ADC radar data
- ZED mini 3D camera
  - Captures depth images as ground truth
- 2D Ball Screw Slider driven by Arduino
  - Moves the radar sensor to form a synthetic-aperture radar structure
- TI mmWave Studio
  - Configures and triggers radar sensor to collect data
- MATLAB
  - Process radar sensor data
  - Radar Data Synthesizer [1]
    - Synthesizes radar data from CAD models
  - Generates intensity images/radar heatmaps
- Python
  - Trains Neural Network models

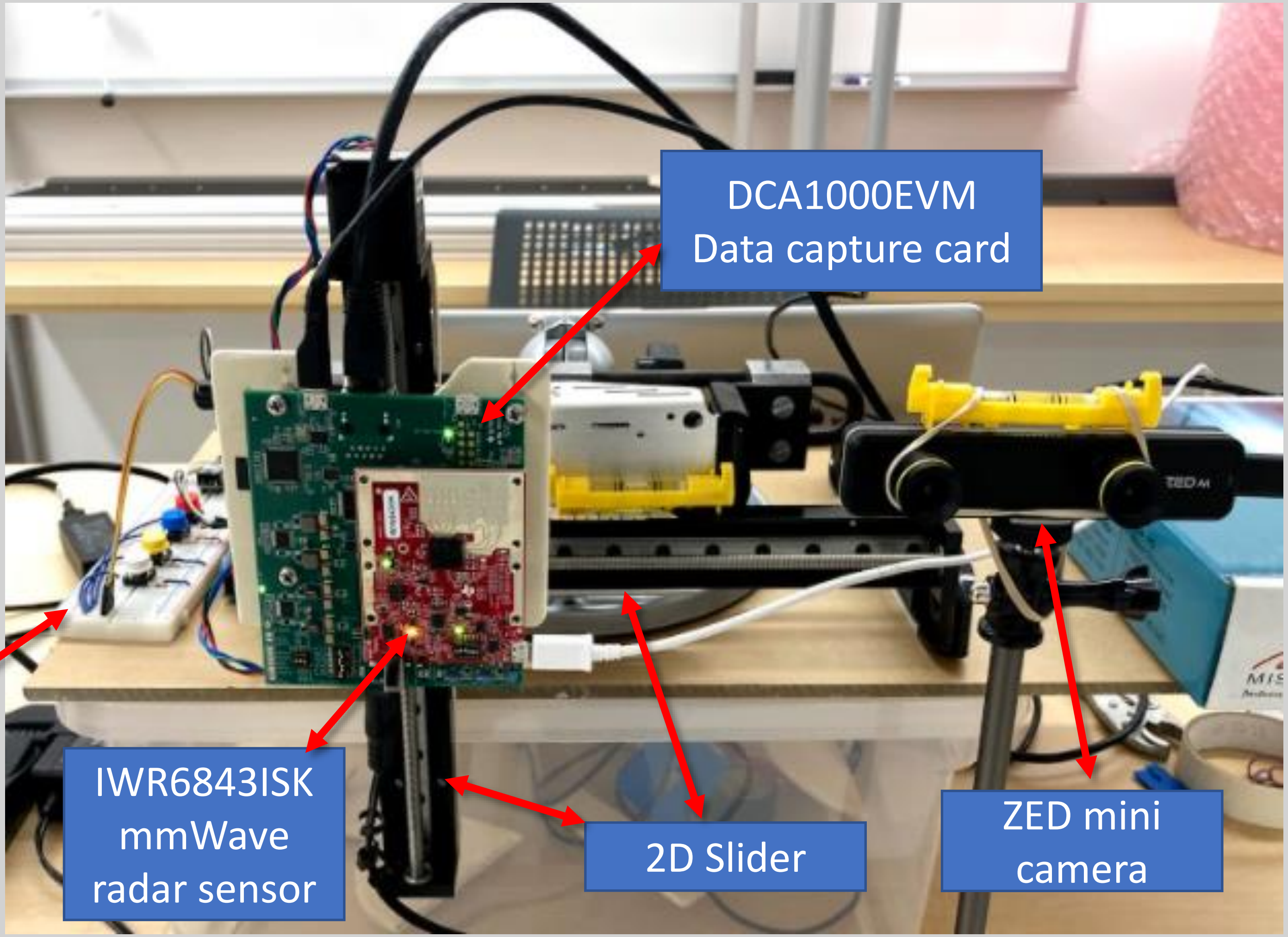
Subsystems: Hardware

- Sliders
  - Repeated positioning accuracy of ± 0.05mm
  - Allow us to accurately move the radar by half of wavelength λ/2 = 2.5mm, to form a SAR.

Arduino Uno with Adafruit motor shield



Slider controller



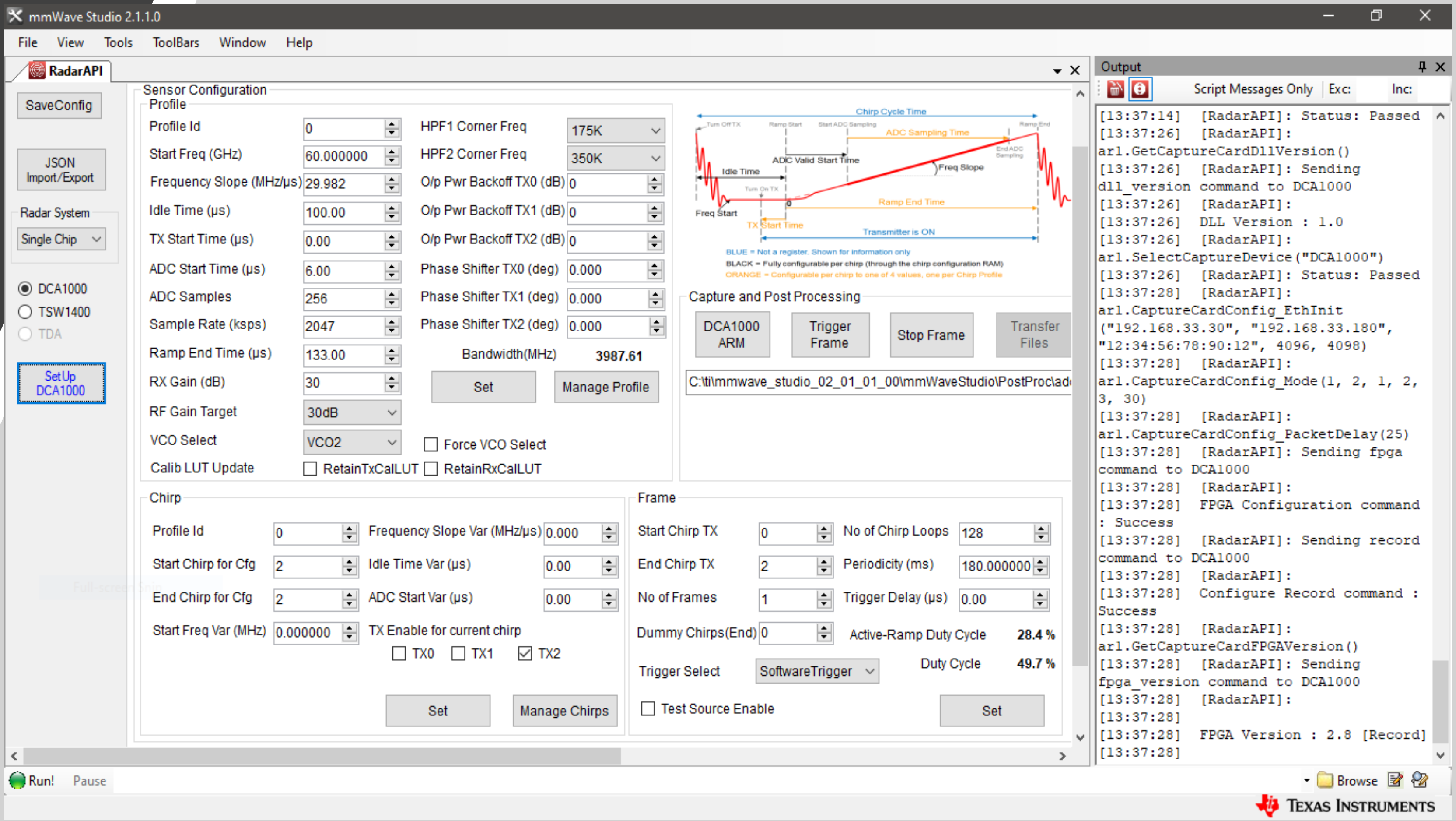
DCA1000EVM Data capture card

IWR6843ISK mmWave radar sensor

2D Slider

ZED mini camera

Subsystem: mmWave Studio



Configure mmWave radar sensor:

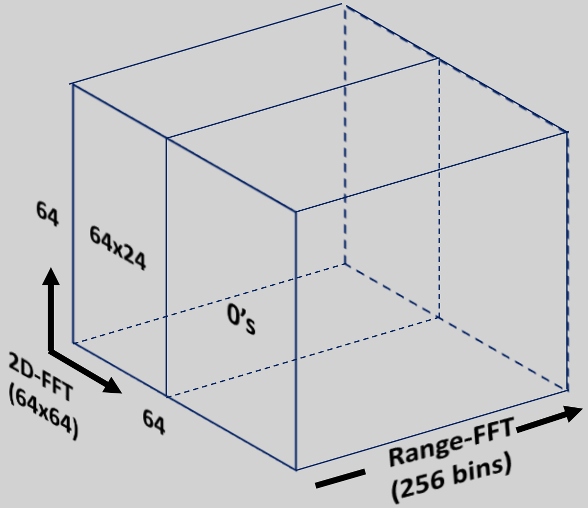
- Start frequency
  - 60GHz
- Sweep slope
  - 29.982MHz/us
- Sample rate
  - 2047ksps
- Number of samples
  - 256
- Bandwidth
  - 3987.61MHz ≅ 4GHz
- Transmitters and receivers
  - 2Tx + 4Rx

Trigger frames to send and capture radar signal

Subsystem: MATLAB Program

HeatmapGenerator.m

1. Apply range-FFT along 256 samples from each virtual antenna
2. Fit data from each range bin (64x24) into a 64x64 matrix, with zero-padding
3. Apply 2D-FFT on each 64x64 matrix
4. Generate heatmaps in each range bin



(screenshots of parts of the program)

```matlab
for range_idx = 1:numADCSamples
    fft_data(:,1:NTX) = rf_data(:,range_idx,:);
    all_fft = fft2(fft_data);
    all_fft = fftshift(all_fft);
    all_fft = flip(flip(all_fft,2));
    temp = abs(all_fft);
    f = figure('visible', 'off');
    heatmap(temp);
    grid off
    colorbar;
    colormap default
    caxis([0 round(m/0.8)]);
    svaddr = '..\intensity_figs\el_az_rg_';
    saveas(f, strcat(svaddr,num2str(range_idx)), 'png')
    disp(range_idx)
end
```

RadarDataSynthesizer.m [1]

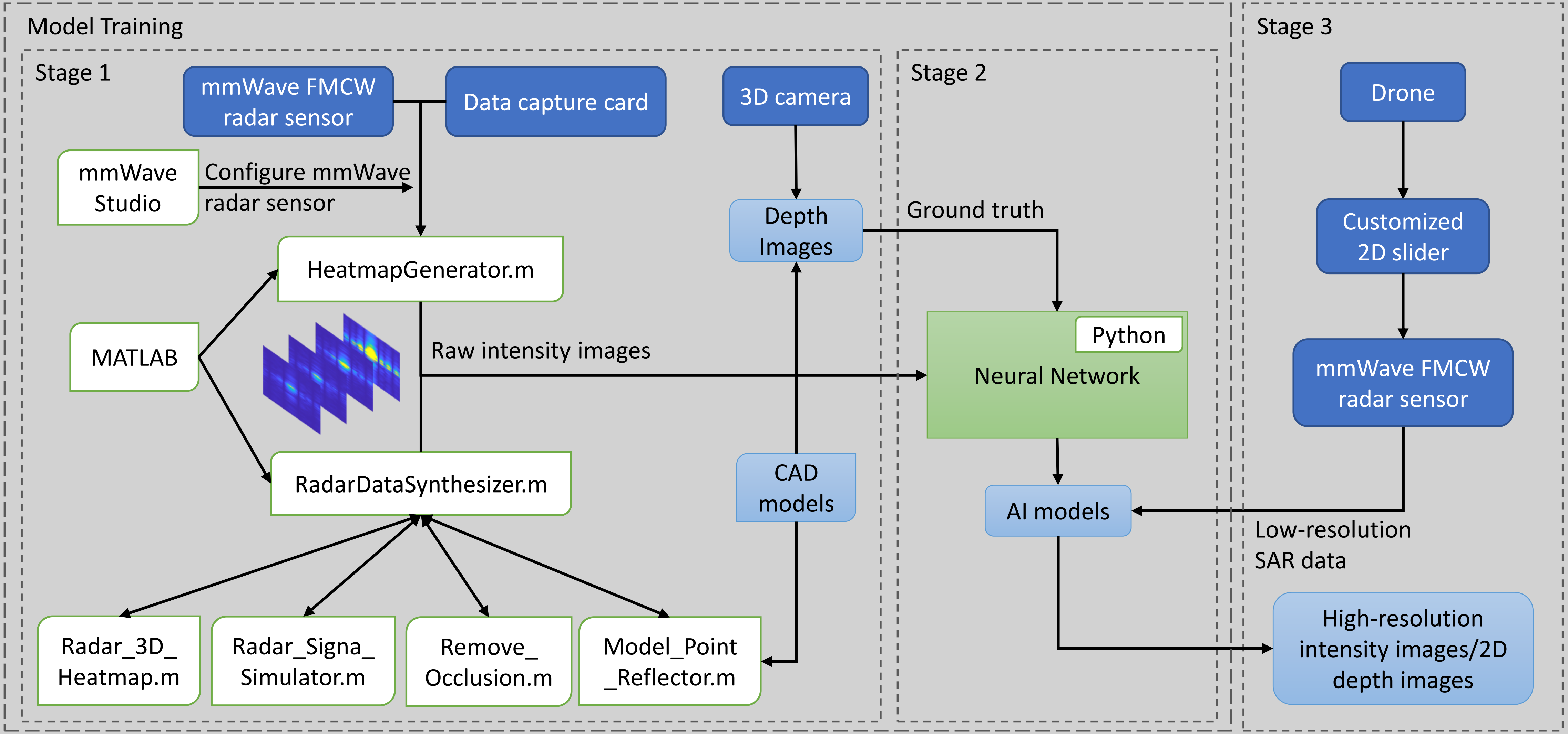
1. Simulate reflector from CAD models of objects
2. Remove occlusion
3. Simulate radar signal
4. Generate radar heatmaps

```matlab

    % Visulize the radar heatmap top view
    radar_heatmap_top = squeeze(max(radar_heatmap,[],3));
    f3 = figure('visible', sp);
    imagesc(radar_heatmap_top);
    set(gca,'XDir','reverse');
    set(gca,'YDir','normal');
    colormap jet; caxis([0 1e11]);
    colorbar;
    %xlabel('Range'); ylabel('Azimuth');
    xlabel('Azimuth'); ylabel('Range'); % 20201129
    set(gca,'FontSize',16) % Creates an axes and sets its FontSize to 18
    svaddr = 'F:\3_Education\UMASS\Courses\droneSLAM\mmWave\hawkeye_synthesizer\figs\md_';
    saveas(f3, strcat(svaddr,num2str(CAD_idx),"_pm_",num2str(ks),"_3RadarHeatmapTopView"), 'png');

    % Visulize the radar heatmap front view
    radar_heatmap_front = squeeze(max(radar_heatmap,[],1));
    f4 = figure('visible', sp);
    imagesc(radar_heatmap_front.');
    set(gca,'XDir','reverse');
    colormap jet; caxis([0 1e11]);
    colorbar;
    xlabel('Azimuth'); ylabel('Elevation');
    set(gca,'FontSize',16) % Creates an axes and sets its FontSize to 18
    svaddr = 'F:\3_Education\UMASS\Courses\droneSLAM\mmWave\hawkeye_synthesizer\figs\md_';
    saveas(f4, strcat(svaddr,num2str(CAD_idx),"_pm_",num2str(ks),"_4RadarHeatmapFrontView"), 'png');
```

Updated Preliminary Budget

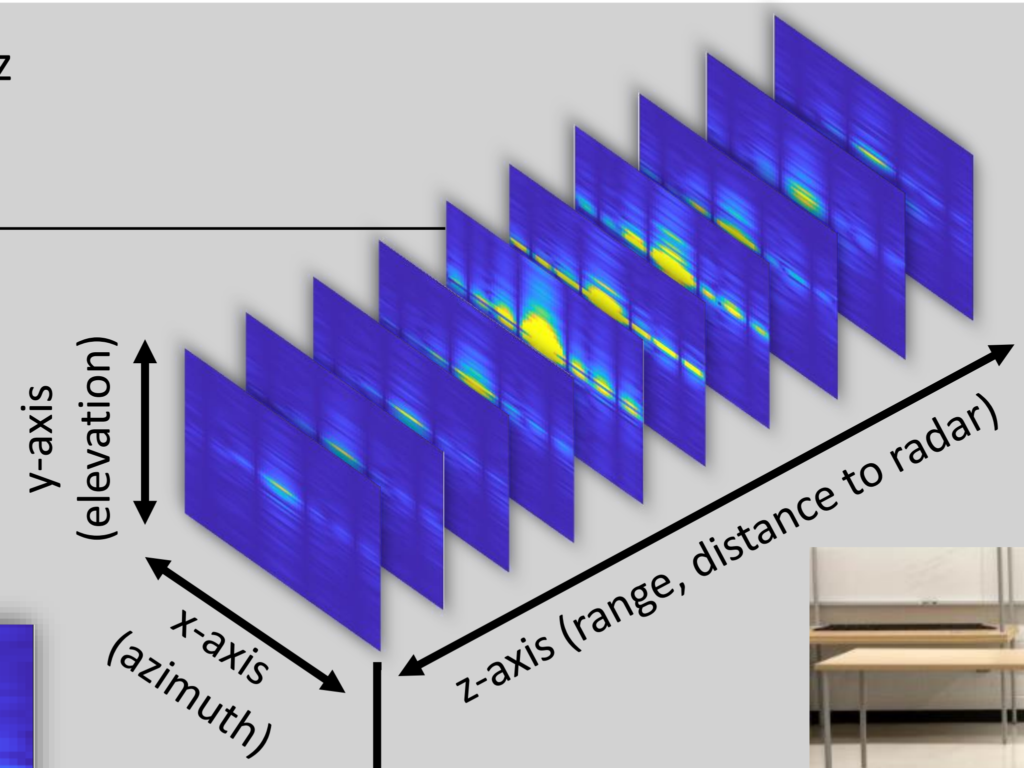
No.	Item	Qty	Unit Price (USD)	Cost (USD)	Description	Note
1	IWR6843ISK	1	135	135	mmWave radar sensor	Previously owned
2	ZED mini	1	399	399	3D camera	Previously owned
3	3D-printed connector	1	N/A	10	Holding radar and camera, extend to a drone	Plan to order
4	**T6x1-200mm Ball Screw Slider**	**2**	**70**	**140**	**For moving the radar sensor horizontally/ vertically in SAR experiments only**	**Recently purchased**
5	**Arduino Uno**	**1**	**23**	**23**	**Slider control**	**Previously owned**
6	**Adafruit motor shield**	**1**	**19.95**	**19.95**	**Motor driver**	**Previously owned**
7	**DCA1000EVM**	**1**	**499**	**499**	**Raw data capture card, for experiments only**	**Previously owned**
8	**Customized 2D slider**	**1**	**N/A**	**25**	**For forming a SAR on a drone**	**Plan to order**
	Total			1250.95		
	Used budget			140	Out of the $1000 budget	
	Final product estimated budget			569		

System Architecture



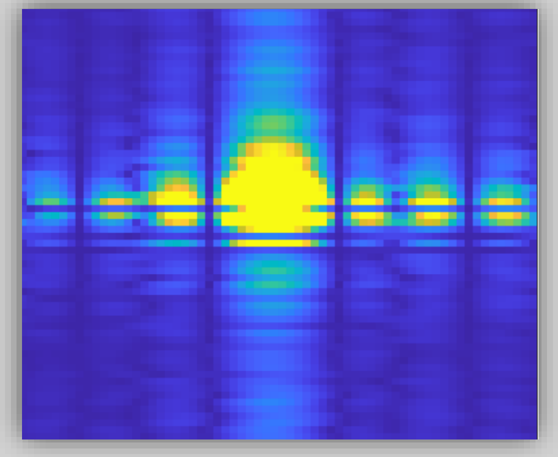
Preliminary Data: Heatmaps from Real Experiments

- Operating frequency: 60GHz-64GHz
- Number of samples: 256
- Size of virtual antennas: 64 x 24
- Antenna spacing: 2.5mm
- Range resolution: 4cm
- Angular resolution:
  - Azimuth = 5°, Elevation = 1.8°

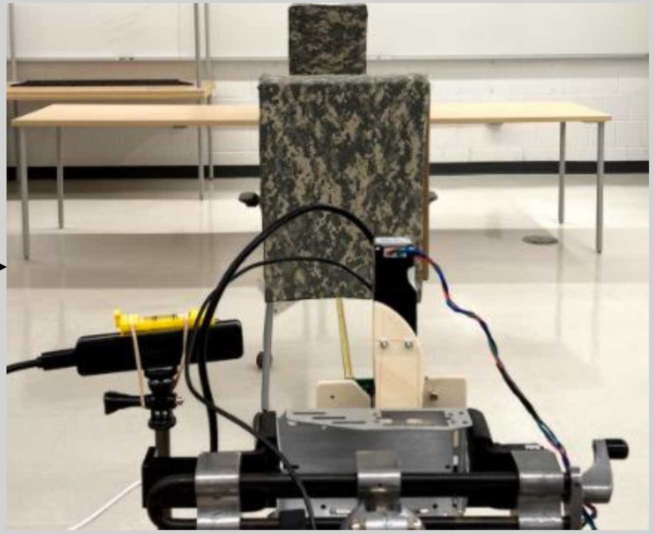


Total 256 intensity images, only 10 are shown here.
(range bins 47-56)

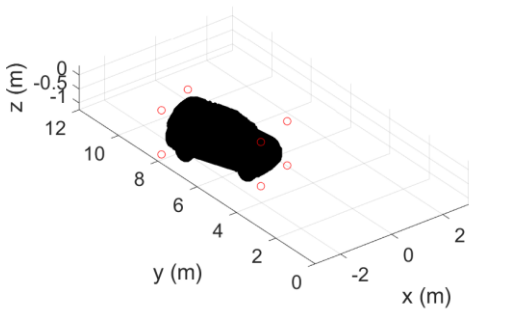
Range bin: 51
Corresponding to distance:
(51-1)*4cm = 200cm



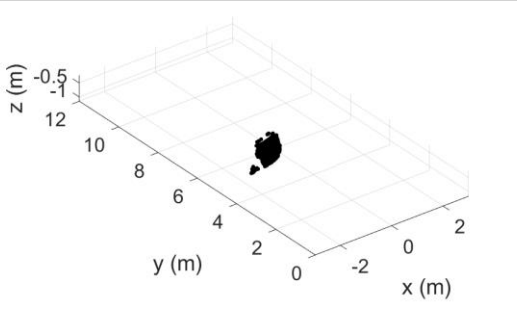
3D Radar intensity version of the scene



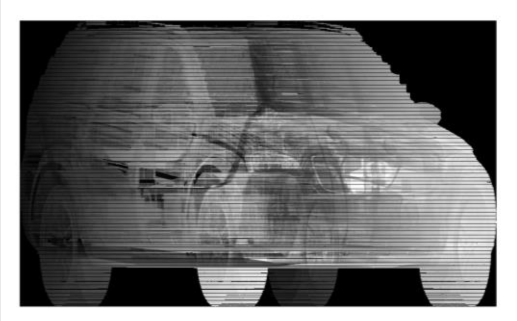
Preliminary Data: Radar Data Synthesizer [1]



(1) CAD model

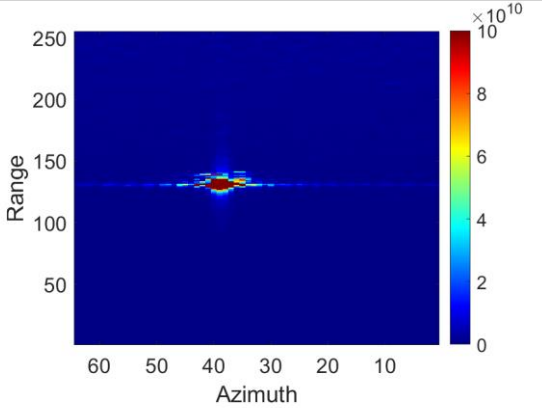


(2) Reflector

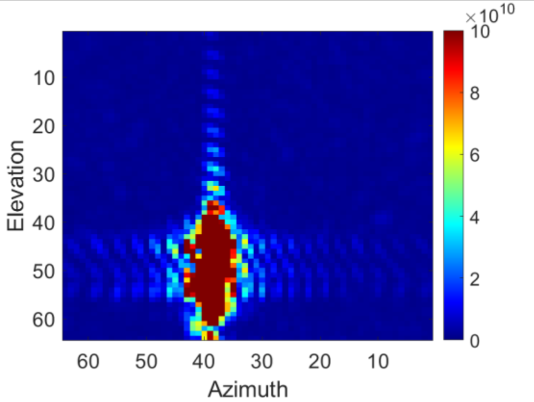


(3) Depth image

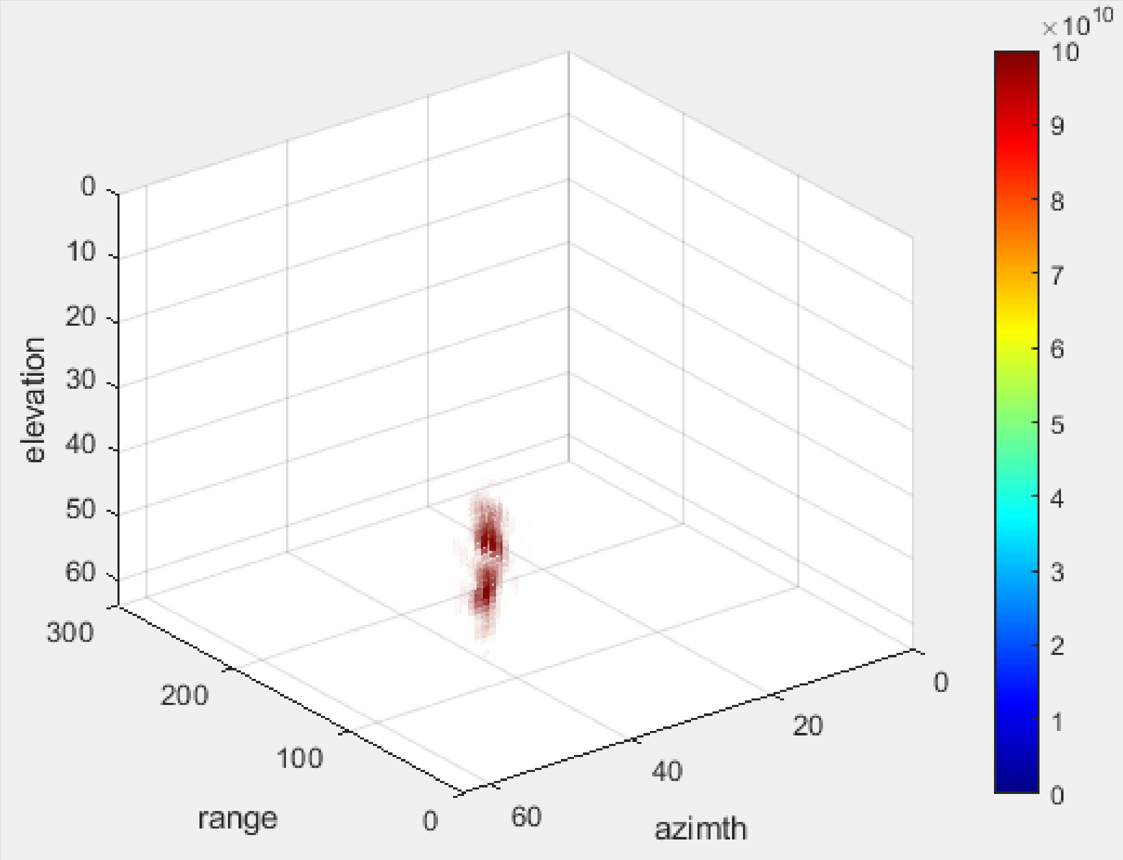
Synthesized radar data



(4) Top view



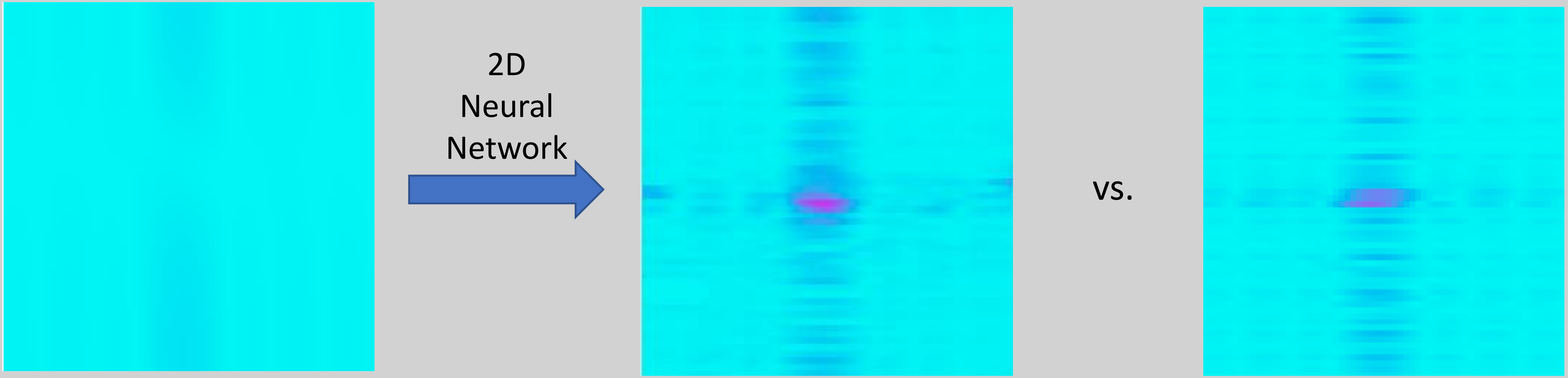
(5) Front view



(6) 3D point cloud

Preliminary Data: Neural Network

- Low-resolution input -> high-resolution output
- 2D-to-2D, pix2pix GAN (Generative Adversarial Network)
- Using only 2x8 virtual antennas to achieve similar resolution from 64x8 virtual antennas.
- Example of our NN producing output from data provided by SuperRF [2]



(1) Input: 2x8 intensity image

(2) Output

(3) 64x8 intensity image

Metrics and Performance Measurement (preview of DVP)

Requirement	Measurement
• **Capability to outline shapes of objects in a scene**	Observe that the shapes of objects are successfully outlined in the 2D depth image output after processing raw radar data.
• **Accurately estimates positions of objects in 3D space**	Compare our result to depth images (ground truth) given by ZED mini camera.
• **Portable (small and lightweight)**	Measure physical dimension and weight (≈ 100g)
• **Mounted on a drone (connector)**	Confirm that a connector is given, and all hardware components can be secured on a drone through this connector.
• **Low-cost**	Calculate the budget for final product (≤ $1000)
• **Easy to use**	Count the steps for configuration and operation (≤ 10)

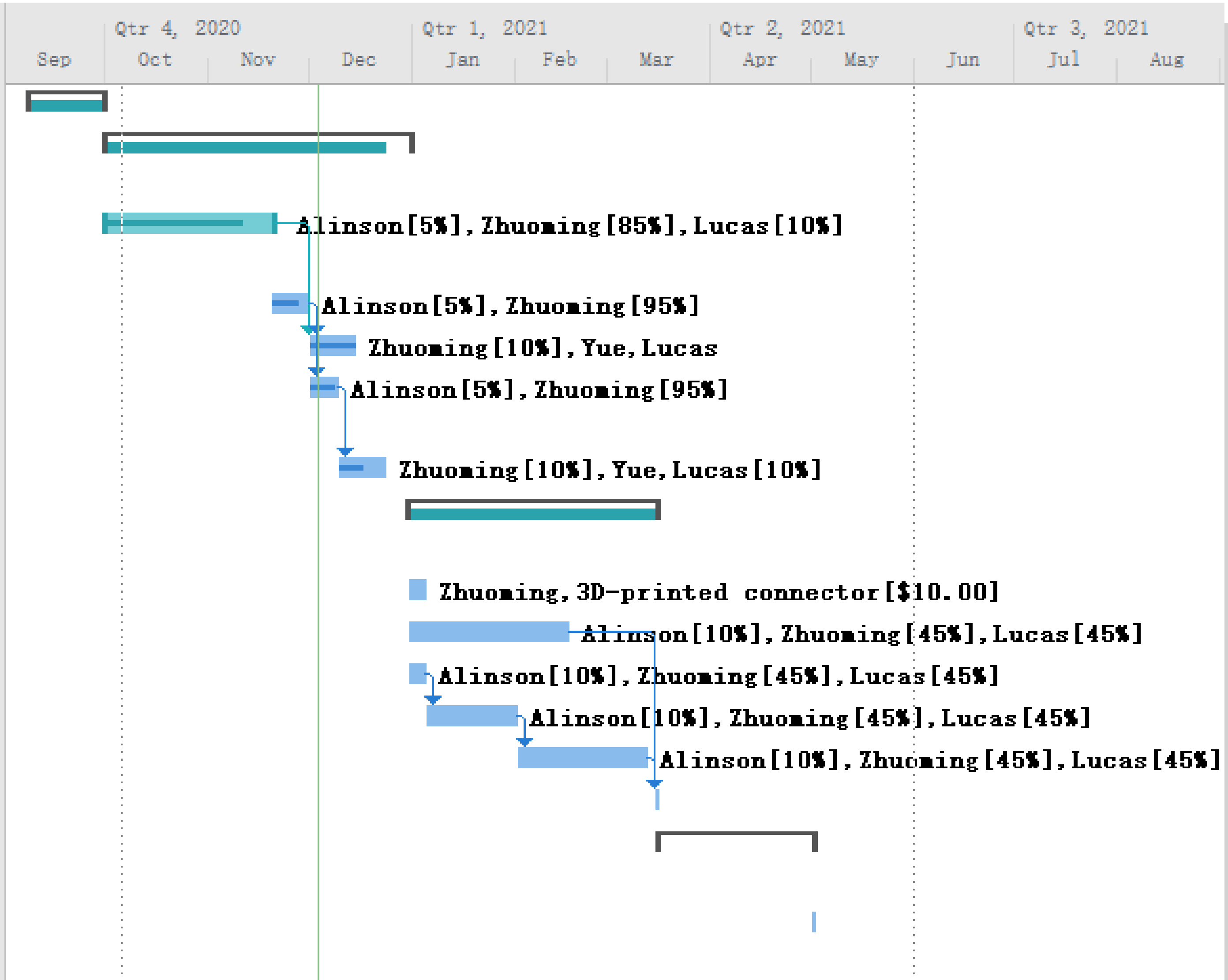
Deliverables

- A 3D-space mapping system
  - Generates high-resolution depth images from sparse raw mmWave radar data
  - Model-training function
    - MATLAB program for generating raw intensity images
    - Neural network for training AI Models
  - 2D slider with control code
  - Modified radar sensor firmware
  - A holder connecting the radar sensor and camera, mounting the system on a drone

Project Management (till Design Validation Presentation)

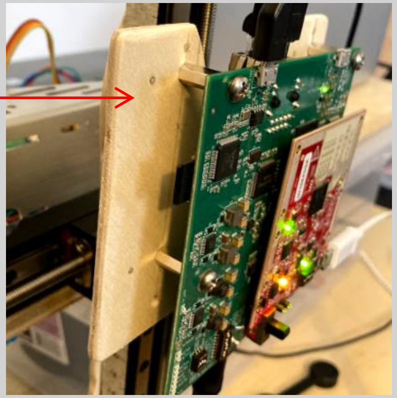
GANTT CHART

	% Work	Task Name	Durati	Start	Finish
2	**100%**	**Research**	**17 days**	**Tue 9/8/20**	**Wed 9/30/20**
9	**45%**	**SAR Experiments and Neural Newwork Training**	**68 days**	**Thu 10/1/20**	**Thu 12/31/20**
10	80%	Collect, analyze and process data	39 days	Thu 10/1/20	Fri 11/20/20
11	80%	Synthesize radar data	7 days	Fri 11/20/20	Mon 11/30/20
12	100%	AI model training (2D)	10 days	Tue 12/1/20	Mon 12/14/20
13	80%	Generate 3D intensity images	7 days	Tue 12/1/20	Wed 12/9/20
14	50%	AI model training (3D)	10 days	Thu 12/10/20	Wed 12/23/20
15	**0%**	**System modification for UAV and tests**	**53 days**	**Thu 12/31/20**	**Mon 3/15/21**
16	0%	3D printing a connector	3 days	Thu 12/31/20	Mon 1/4/21
17	0%	System test 1	34 days	Thu 12/31/20	Tue 2/16/21
18	0%	Flight test room setup	3 days	Thu 12/31/20	Mon 1/4/21
19	0%	Flight test	20 days	Tue 1/5/21	Mon 2/1/21
20	0%	System test 2	29 days	Tue 2/2/21	Fri 3/12/21
21	0%	Design Validation	1 day	Mon 3/15/21	Mon 3/15/21
22	**0%**	**System Optimization and Tests**	**35 days**	**Tue 3/16/21**	**Sat 5/1/21**
23	0%	Final product ready	1 day	Sat 5/1/21	Sat 5/1/21



Anticipated Problems and Solutions

- Access to 3D printers on campus
  - Temporarily using handcrafted wooden connectors
  - Order 3D-printing online or handcrafting with acrylic board.



- UAV flight tests
  - Safety issue
    - Wear eye protectors and gloves
  - Flight-test room availability
    - Outdoor public facility with net-covering
  - Hardware availability
    - Use another ZED mini (not the one on UAV) to capture depth images as ground truth for scene reference if Kinect or OptiTrack system are not available.

Ethical Considerations

- Privacy issue when conducting outdoor experiments
  - Must ask for a permission if private properties are involved
  - Keep the camera off in public areas if it is not necessary to turn it on, or if someone doesn’t feel comfortable in front of it.
- Covid-19 Guidelines
  - Masks on
  - Keep social distance

Thank you

- Questions?

- Reference

  - [1] Junfeng Guan, Sohrab Madani, Suraj Jog, and Haitham Hassanieh. 2020. High Resolution Millimeter Wave Imaging For Self-Driving Cars. IEEE CVPR (2020).
  - [2] Shiwei Fang and Shahriar Nirjon. 2020. SuperRF: Enhanced 3D RF Representation Using Stationary Low-Cost mmWave Radar. In International Conference on Embedded Wireless Systems and Networks (EWSN)..., Vol. 2020. NIH Public Access, 120.