3D-Space Mapping via UAV-based RF sensing

Design Validation Presentation

03/30/2021

Team 4

Customer Mentor/Technical Manager:
Dr. Honggang Zhang

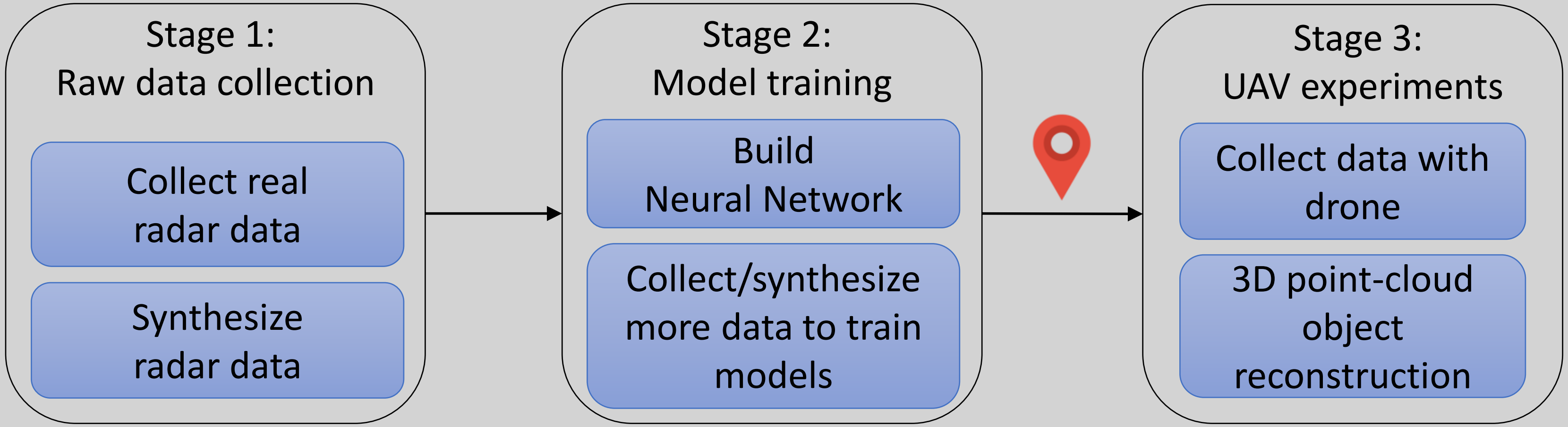
Zhuoming Huang
Alinson Sanquintin

Team Roles

- SAR Experiment team:
  - Zhuoming Huang
    - Collecting and synthesizing radar and camera sensor data for model training.
    - Subsystem tests and analyses.
    - Drone development
  - Alinson Sanquintin
    - Creates CAD models and converts them into point-cloud format.
    - Subsystem tests, assists with SAR experiments and data processing.

- Neural Network team (external):
  - Yue Sun ~~and Lucas Lomba~~
    - Building Neural Networks to train AI models and generate 3D radar intensity maps/2D depth images.

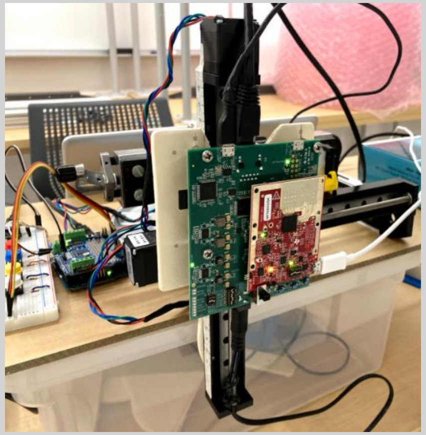
Project Progress

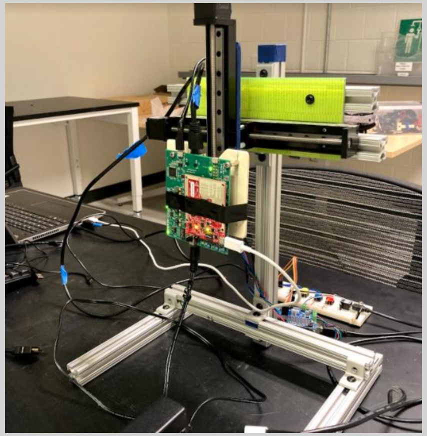


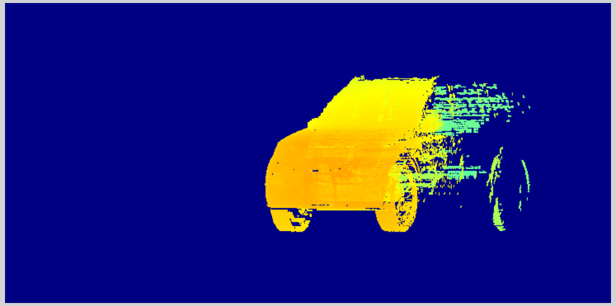
- **Previous State:**
  - Built a 2D-sliding mechanism for raw data collection with an SAR (Synthetic-aperture Radar) structure.
  - Built a Neural Network to produce 2D full-scale intensity maps from 2D 2-snapshot intensity maps [1].
- **Current State:**
  - Built Neural Networks to produce 2D depth images from 3D radar intensity maps and 3D full-scale intensity maps from 3D 2-snapshot intensity maps.
  - Using CAD models to synthesize radar signal, radar intensity maps and depth images to train deep neural network models [2].
  - Moving from stage 2 to stage 3
  - Developing the drone with a customized 2D sliding mechanism.
  - Reconstructing objects in 3D point-cloud from multiple 2D depth images.
- **Next State:**
  - Modify radar firmware to collect radar data without Data capture card.
  - Flight tests and data collection with drone.

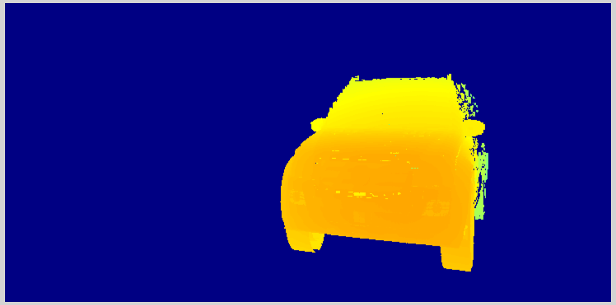
Design Improvements

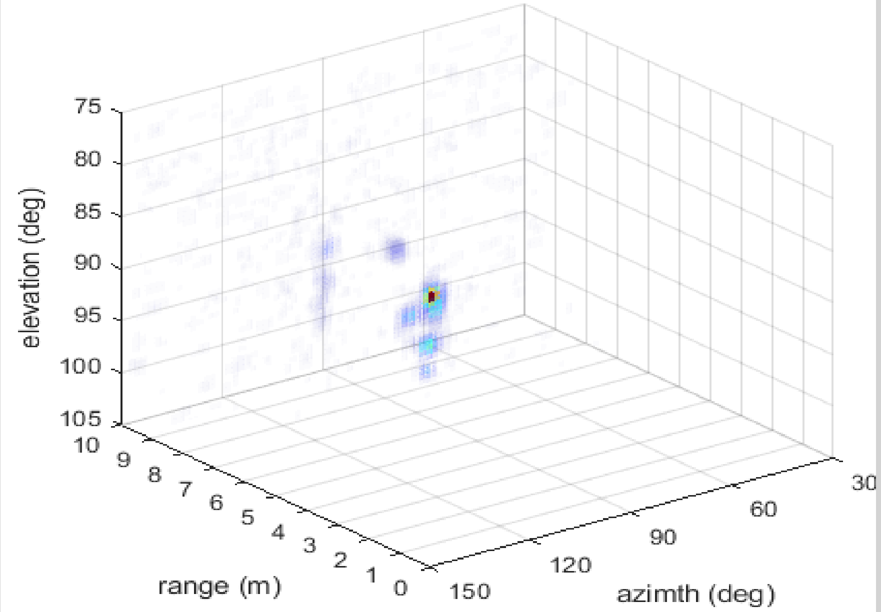
1. Stable and adjustable frame for SAR experiments
2. Synthesizing depth images:
   Orthographic projection -> Perspective Projection
3. Model training:
   Spherical Coordinates -> Cartesian Coordinates
   (to match the coordinate system of camera)

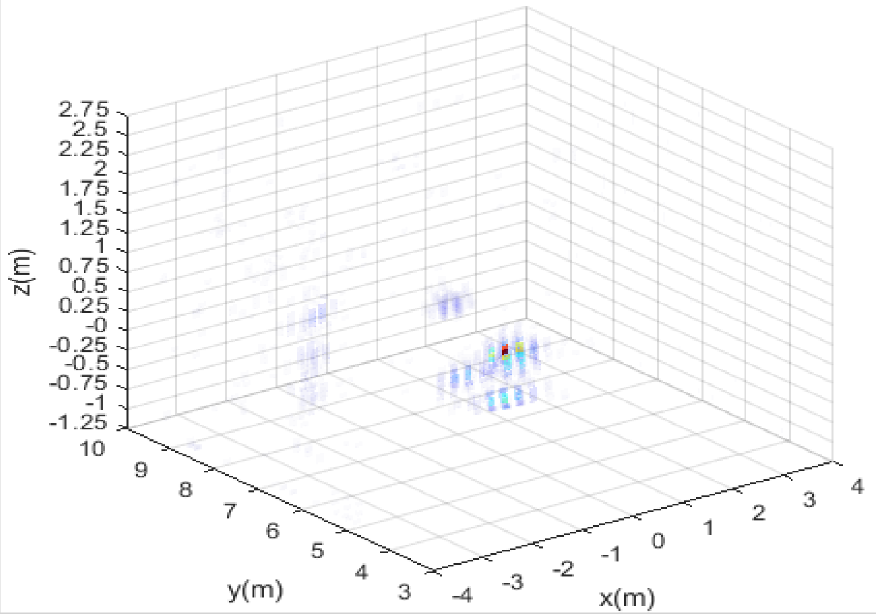




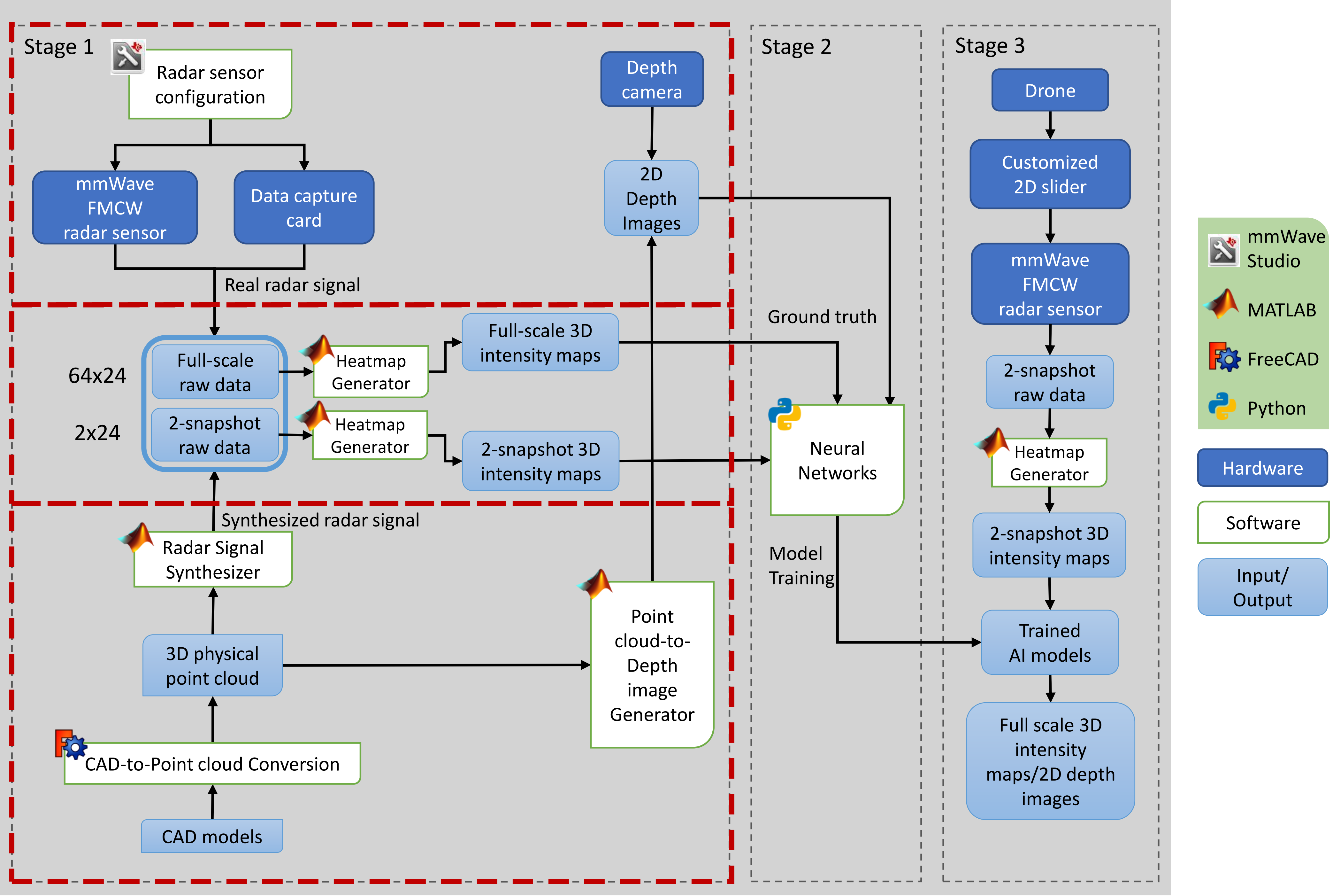




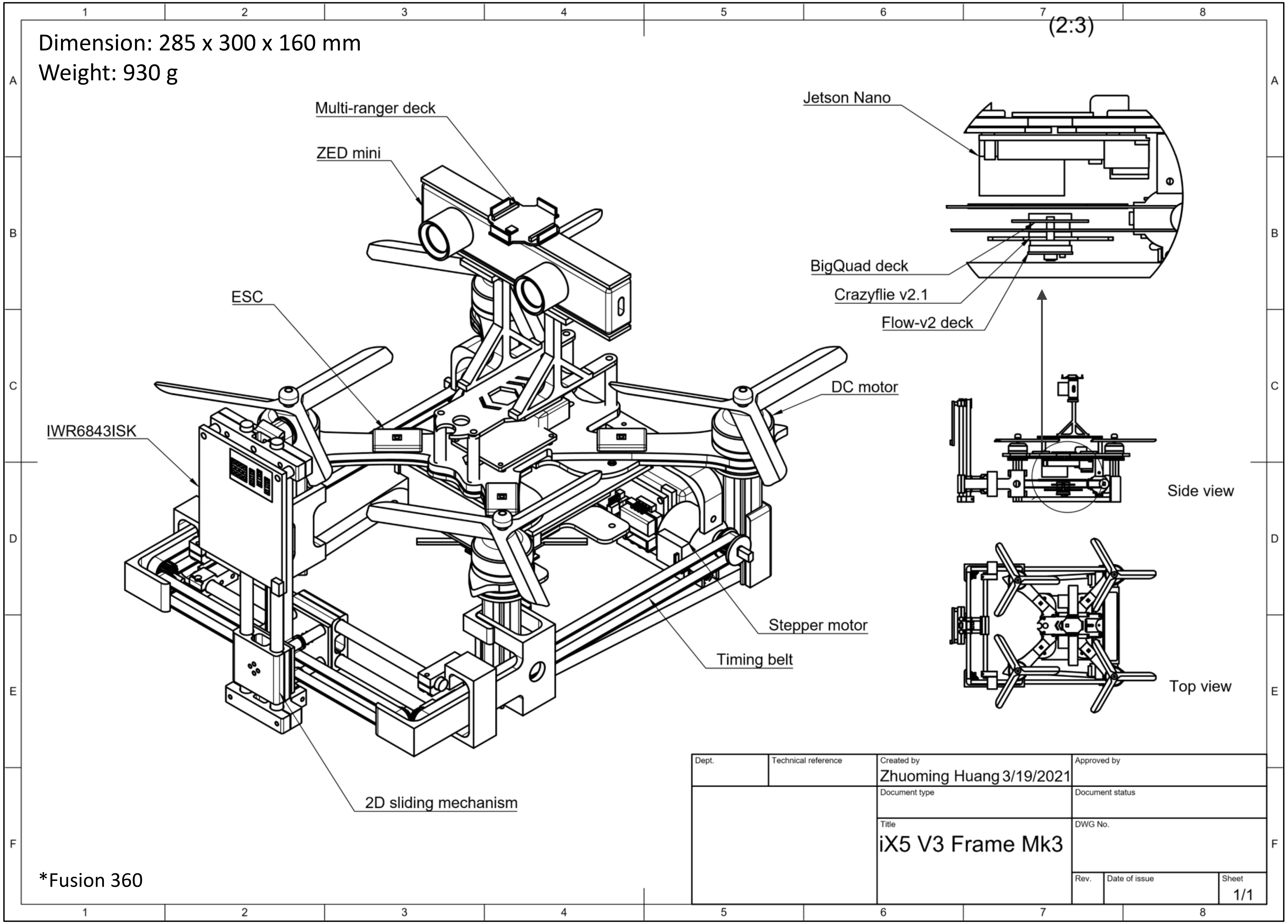




System Architecture



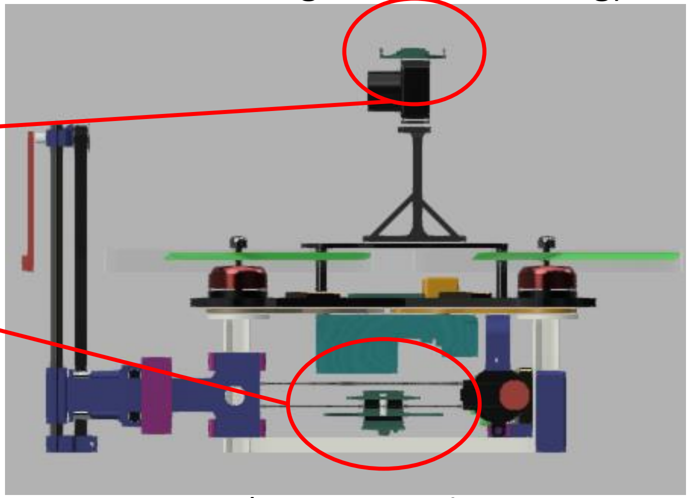
Drone Design



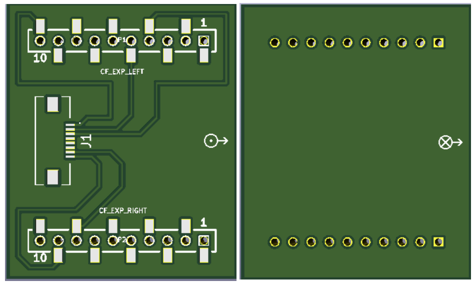
PCB Design

A pair of deck connectors with an FFC cable are specifically used to connect the Multi-ranger deck on the top to the other Crazyflie components (e.g., Flow-v2 deck) at the bottom of the drone.

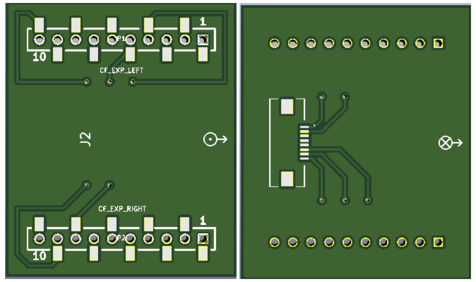
(Measures distance to ceiling and surrounding)



(Measures distance to the ground)



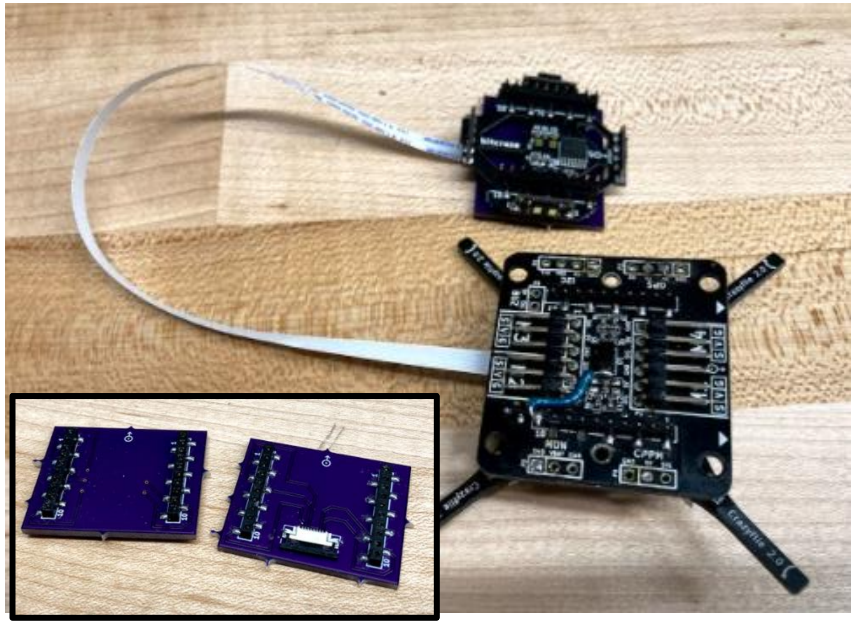
Deck connector A (front/back)



Deck connector B (front/back)

Connection test: no error reported, all decks are fully functioning

deck			
bcAIDeck	uint8_t	RO	0
bcBigQuad	uint8_t	RO	1
bcBuzzer	uint8_t	RO	0
bcCPPM	uint8_t	RO	0
bcDWM1000	uint8_t	RO	0
bcFlow	uint8_t	RO	0
bcFlow2	uint8_t	RO	1
bcGTGPS	uint8_t	RO	0
bcLedRing	uint8_t	RO	0
bcMultiranger	uint8_t	RO	1
bcOA	uint8_t	RO	0
bcUSD	uint8_t	RO	0
bcZRanger	uint8_t	RO	0
bcZRanger2	uint8_t	RO	1
bdLighthouse4	uint8_t	RO	0

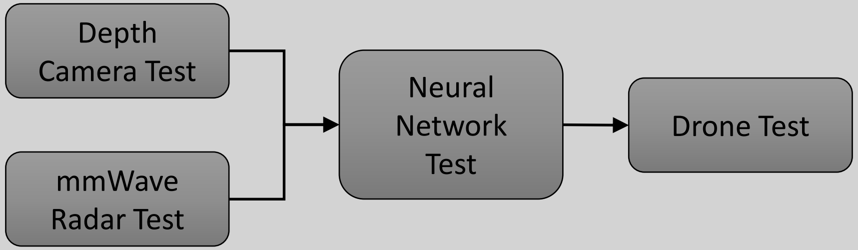


System Demo Video

https://www.youtube.com/watch?v=uxX2rqvvrc0 (1:52)

Design Validation

System Validation Process



- **Test 1: Depth camera**
  - Reference: OptiTrack
  - In a room with nonuniform light, place markers on the corners, edges, and surfaces of objects (e.g., box, desk). Capture the depth image with depth camera, and record positions of markers with OptiTrack. Measure and compare the distance from depth camera to each marker over 100 frames.
- **Test 2: mmWave Radar sensor**
  - Reference: OptiTrack
  - In a room, place objects at some distance. For each object, place markers at the four corners of the surface facing towards the radar sensor. Measure and compare the distance from radar sensor to that surface over 100 frames/chirps.
- **Test 3: Neural Network**
  - Reference: Synthesized 2D depth images
  - Extract only 2 snapshots of synthesized radar data to generate the 3D intensity maps.
  - Using 2475 pairs of 3D radar intensity maps and 2D depth images (synthesized from CAD car models [2]) to train an AI model.
  - Input 25 sets of 3D radar intensity maps to the model, compare the AI generated 2D depth images to synthesized 2D depth images using loss function.
- **Test 4: Power supply of Drone**
  - Run the motors under different settings of throttle, record the voltage of battery every 5 minutes.

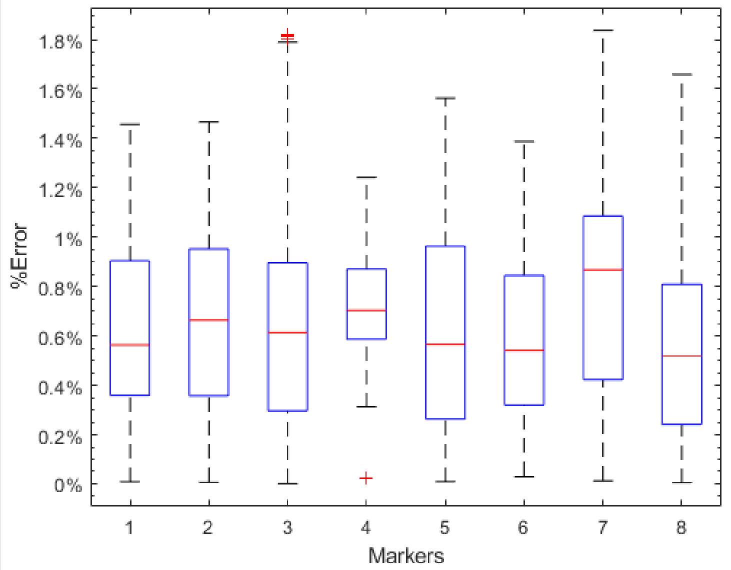
OptiTrack:
A set of fixed optical camera sensors that can provide accurate measurements with positional error < 0.3mm, and rotational error < 0.05°

*Thanks Prof. Rahaim for his OptiTrack system

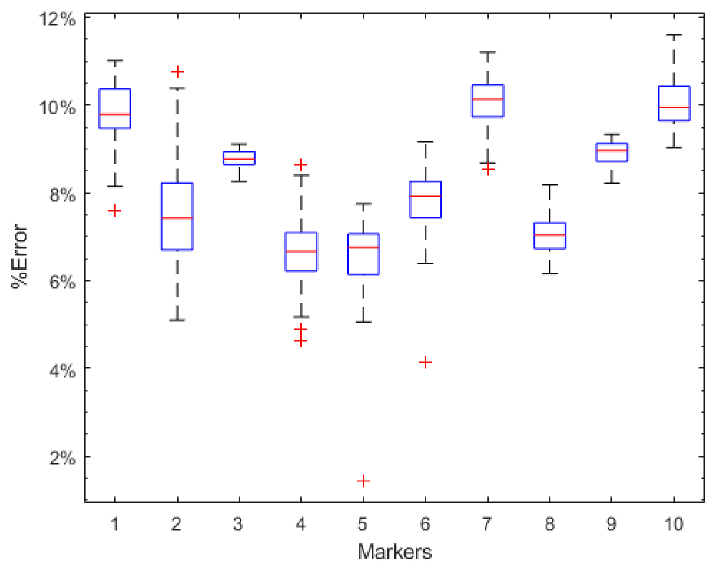
Validation Data
– Depth Camera

Accuracy in distance measurements

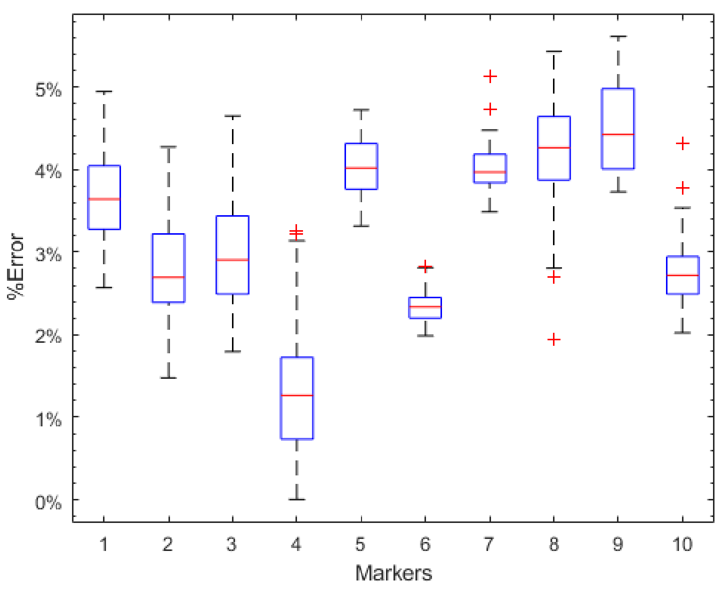
1. High brightness – High contrast



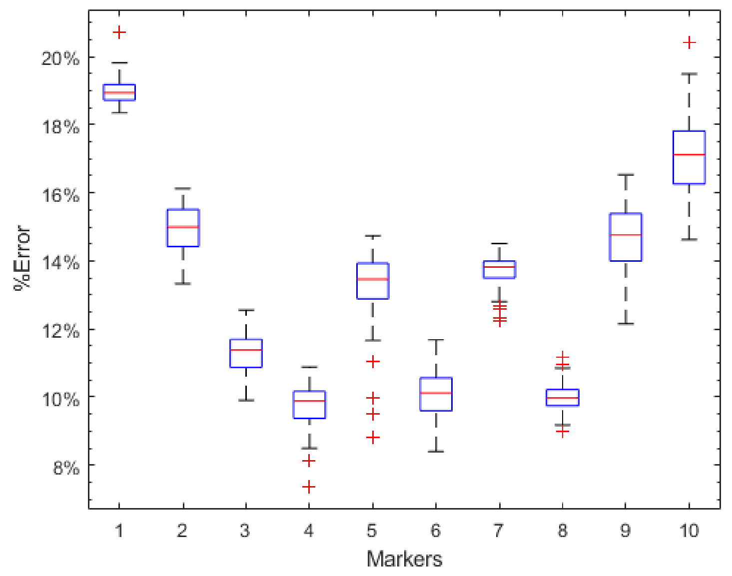
2. High brightness – Low contrast



3. Low brightness – High contrast



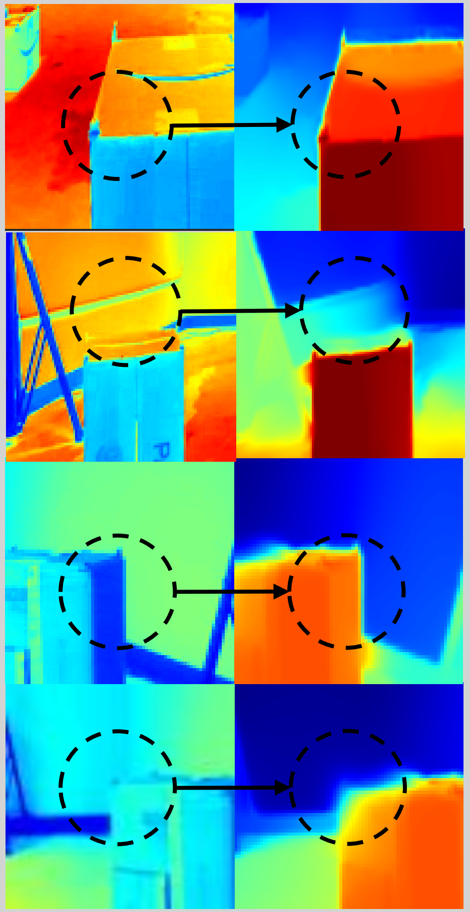
4. Low brightness – Low contrast



Contrast / Brightness	High	Low
High	**<1.8%**	**<11.5%**
Low	**<5.6%**	**<21.0%**

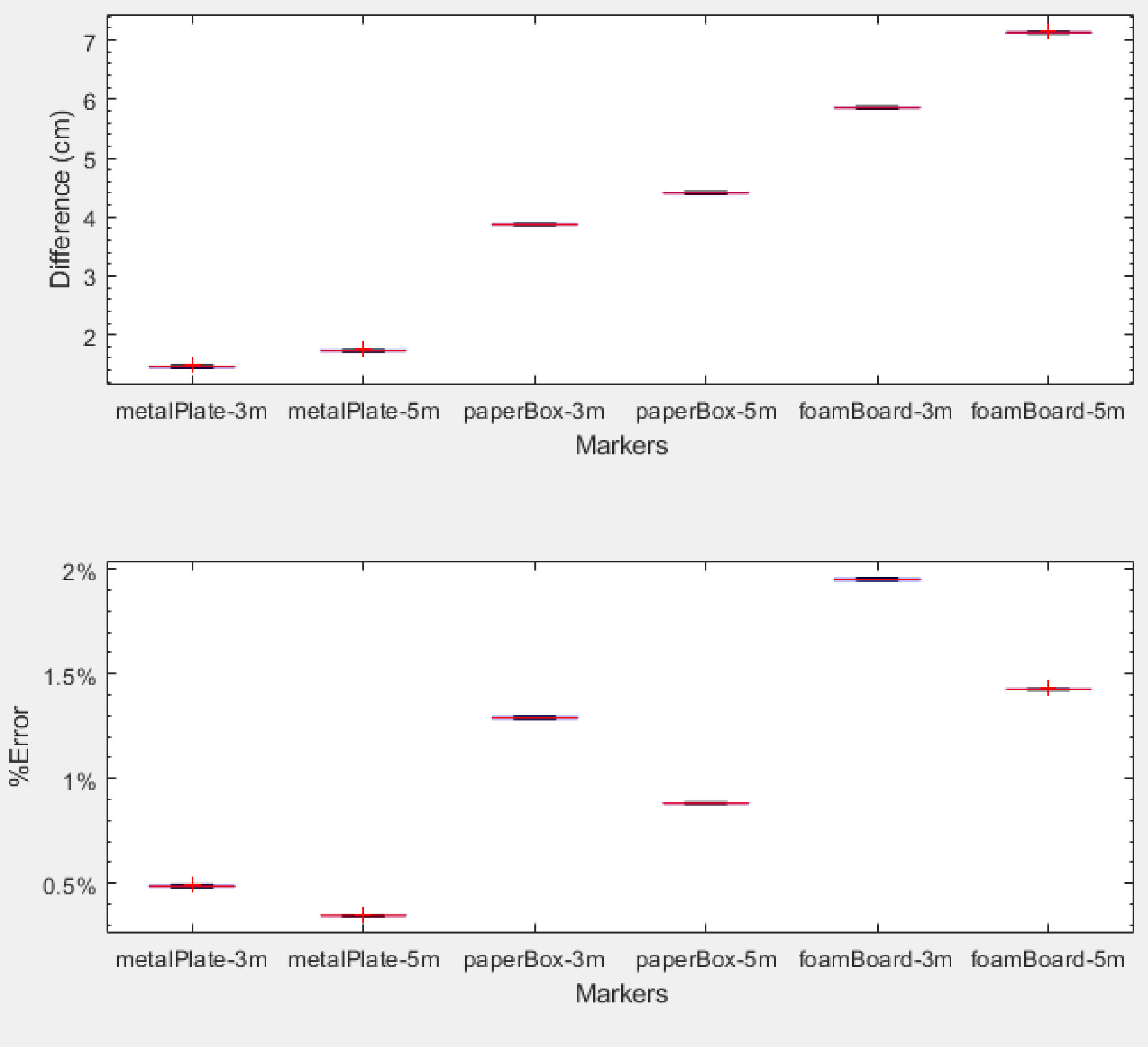
Brightness images | Depth images

1.
2.
3.
4.



Validation Data – mmWave Radar

Distance measurement comparison



- Antenna array size: 64 x 24
- Range resolution ≅ 3.8cm
- Elevation angular resolution ≅ 1.8°
- Azimuth angular resolution ≅ 4.8°

Tested 3 materials:

- Metal plate: strong reflection
- Paper box: weak reflection
- Foam board: multi-path reflection

	Metal plate		Paper box		Foam board	
	Diff(cm)	Error	Diff(cm)	Error	Diff(cm)	Error
3m	**1.43**	**0.48%**	**3.85**	**1.29%**	**5.87**	**1.95%**
5m	**1.73**	**0.34%**	**4.43**	**0.88%**	**7.15**	**1.42%**

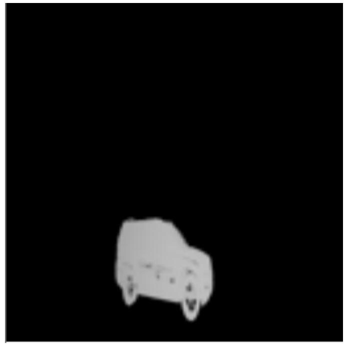
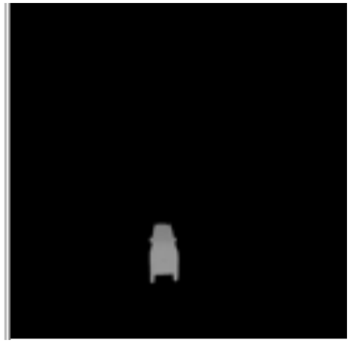
Angle measurement result

Azimuth	Elevation
<16.5%	**<4.3%**

Validation Data – Neural Network

Workflow: 2-snapshot 3D radar intensity map -> 2D depth image

Examples of results:

	Good	Acceptable	Bad
True depth images (synthesized from CAD car models[2])			
AI-generated depth images			
	Matched in color, size and orientation	Matched in color. Similar size and orientation	Wrong size and orientation

Trained	**2475**	
Verified	**25**	
Good	14	56%
Acceptable	6	80%
Bad	5	

Generator losses	
G_GAN:	0.693
G_L1(*1000):	2.861
G_Lp(*20):	21.452
Discriminator losses	
D_real:	0.440
D_fake:	0.693

Validation Data – Drone

Battery info: **11.1V**, 20.0Wh, 1800mAh
Room temperature during tests: 17°C
Tested without running other devices (e.g., Jetson Nano, ZED mini camera, IWR6843ISK radar sensor)

50% Throttle

Time (min)	Battery Voltage (V)
0	12.53
5	12.46
10	**12.35**
15	11.72
20	11.15

75% Throttle

Time (min)	Battery Voltage (V)
0	12.51
5	12.40
10	**11.99**
15	11.16
20	10.95

100% Throttle

Time (min)	Battery Voltage (V)
0	12.60
5	11.73
10	**11.34**
15	11.13
20	9.65

To do next: Power consumption test with running all devices

Updated Preliminary Budget

Pre-owned
Have purchased
Newly added
One time use
Plan to order

#	Item	Qty	Unit Price	Cost	Description	Status
1	IWR6843ISK	1	$135.00	$135.00	mmWave radar sensor	Owned
2	ZED mini	1	$399.00	$399.00	3D depth camera	Owned
3	T6x1-200mm Ball Screw Slider	2	$70.00	$140.00	For moving the radar sensor horizontally/ vertically in SAR experiments only	Purchased
4	Arduino Uno	1	$23.00	$23.00	Slider control	Owned
5	Adafruit motor shield	1	$19.95	$19.95	Motor driver	Owned
6	DCA1000EVM	1	$499.00	$499.00	Raw data capture card, for experiments only	Owned
7	Customized small 2D sliding mechanism	1	N/A	$25	For forming an SAR on a drone, including 3d-printed parts, timing belts, stepper motors	Purchased
8	**T-slotted rails**	**2**	**$20.00**	**$40.00**	**Frame that holds ball screw sliders and radar sensors for SAR experiments**	**Purchased**
9	**OSHPARK PCBs**	**1**	**$20.80**	**$20.80**	**Deck connectors**	**Purchased**
10	**Wurth Elektronik FFC connector**	**10**	**$1.33**	**$13.30**	**To be used on PCBs**	**Purchased**
11	**Jetson Nano**	**1**	**$59.00**	**$59.00**	**Computing unit on drone**	**Owned**
12	**Jetson Nano cooling fan**	**1**	**$13.70**	**$13.70**		**Purchased**
13	**Crazyflie set**	**1**	**$327.00**	**$327.00**	**Flight control, including Crazyflie v2.1, BigQuad deck, flow-v2 deck, and multi-ranger deck**	**Owned**
	Total			*$1714.75*	*Model training + UAV sensing equipment*	
	Used budget			*$252.80*	*Out of the $1000 budget*	
	Final product estimated budget			***$965.80***	***UAV sensing equipment***	

Deliverables

- A 3D-space mapping system
  - Goal: Generates depth images from sparse raw mmWave radar data.
  - Model-training
    - Raw data collecting mechanism (Fig. 1)
    - MATLAB program for generating 3D radar intensity images and 2D depth images.
    - Neural networks for training AI Models
  - UAV-sensing
    - Drone with SAR mechanism holding and moving the radar sensor and depth camera (Fig. 2)
    - Modified radar sensor firmware
    - Live data collection via radar sensor and depth camera
    - Real-time generation of depth images

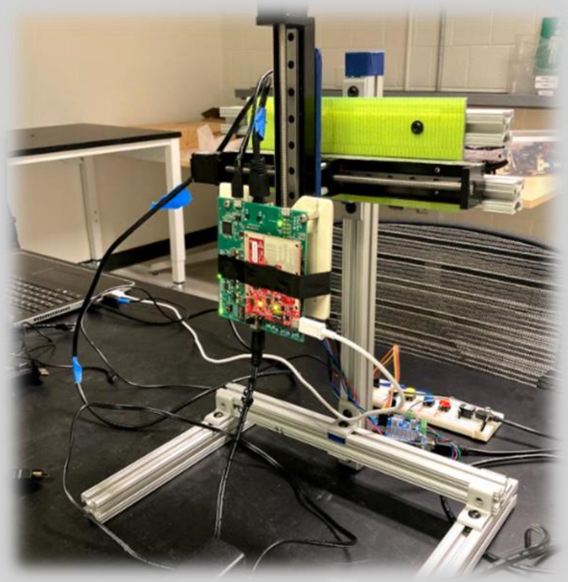


Fig. 1

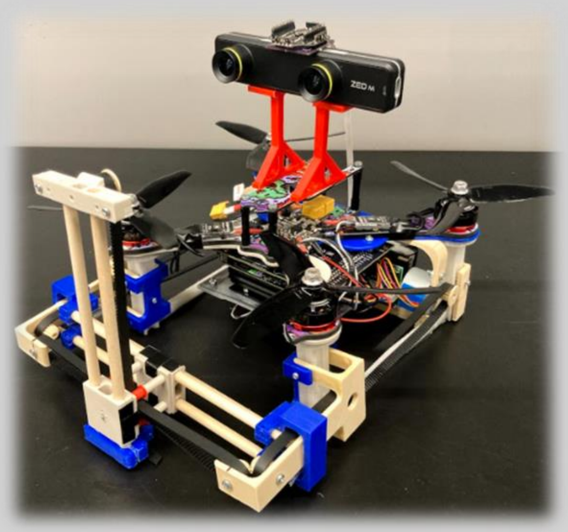


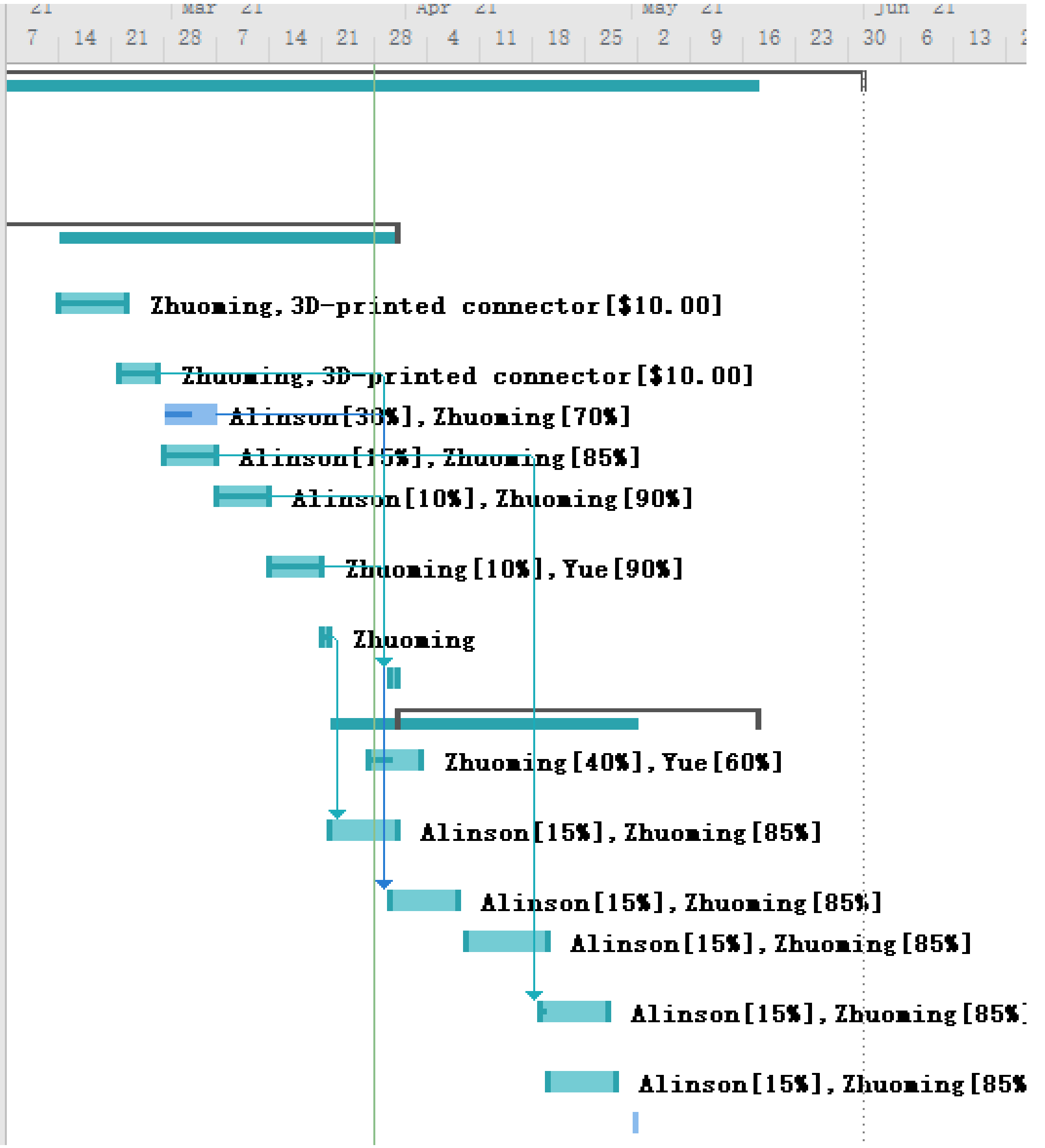
Fig. 2

Anticipated Problem

- **Safety issue during flight tests**
  - Check battery status
  - Wear eye protectors and gloves
  - Test with manual mode first
- **Stabilization problem of the drone**
  - Upgrade the motors, propellers, and power supply and distribution system.
  - Test in outdoor facility
- **Less accurate distance measurements by depth camera**
  - Make sure a high visibility for depth capturing during the model training process.
  - Use the depth camera to obtain the shape of objects.
  - Use the accurate measurements from mmWave radar sensor.

Project Management

% Work	Task Name	Duration	Start	Finish
1	77%	Protable 3D Mapping System Design	194 days	Tue 9/8/20	Mon 5/31/21
2	100%	Research	17 days	Tue 9/8/20	Wed 9/30/20
9	100%	SAR Experiments and Neural Newwork Training	68 days	Thu 10/1/20	Thu 12/31/20
15	90%	System verification and UAV development	48 days	Mon 1/25/21	Tue 3/30/21
16	100%	3D printing drone slider system design	7 days	Sun 2/14/21	Mon 2/22/21
17	100%	PCB design	5 days	Mon 2/22/21	Fri 2/26/21
18	80%	Flight test room setup	6 days	Sun 2/28/21	Sat 3/6/21
19	100%	Radar Sensor Verificaiton Test	7 days	Sun 2/28/21	Sat 3/6/21
20	100%	Camera Sensor Verificaiton Test	7 days	Sun 3/7/21	Sat 3/13/21
21	100%	Neural Network Verificaiton Test	7 days	Sun 3/14/21	Sat 3/20/21
22	100%	Drone Power test	1 day	Sun 3/21/21	Sun 3/21/21
23	0%	Design Validation	1 day	Tue 3/30/21	Tue 3/30/21
24	4%	System Optimization and Tests	35 days	Wed 3/31/21	Mon 5/17/21
25	35%	Scene reconstruciton w/ multiple depth images	6 days	Sat 3/27/21	Fri 4/2/21
26	0%	Drone stablization test (outdoor)	7 days	Mon 3/22/21	Tue 3/30/21
27	0%	Drone accuracy test (indoor)	7 days	Tue 3/30/21	Wed 4/7/21
28	0%	Radar Sensor firmware modification	7 days	Fri 4/9/21	Mon 4/19/21
29	10%	Automation code for raw data collection	7 days	Mon 4/19/21	Tue 4/27/21
30	0%	System Optimization	7 days	Tue 4/20/21	Wed 4/28/21
31	0%	Final product ready	1 day	Sat 5/1/21	Sat 5/1/21



Satisfaction Survey

Description	Satisfaction grade (1 lowest to 5 highest)		
	Prof. Zhang	Zhuoming	Alinson
How current project responds to the customer requirements?	5	5	5
Verification/validation tests being carried out	5	4	5
Team communication, data and document transparency	5	5	5
Team member collaborations and work distribution	5	5	5
Team work ethics and innovation efforts	5	5	5

- All finished parts of the project met the requirements.
- Everyone paid great effort to catch up with the schedule.
- Some test conditions need to be quantified.
- Need more tests and time.

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.