Fast mmWave RF 3D-Object Reconstruction in Low-Visibility Environment via UAV Platform

Final Product Presentation

05/14/2021

Team 4

Customer Mentor/Technical Manager:

Dr. Honggang Zhang

Zhuoming Huang(Senior)

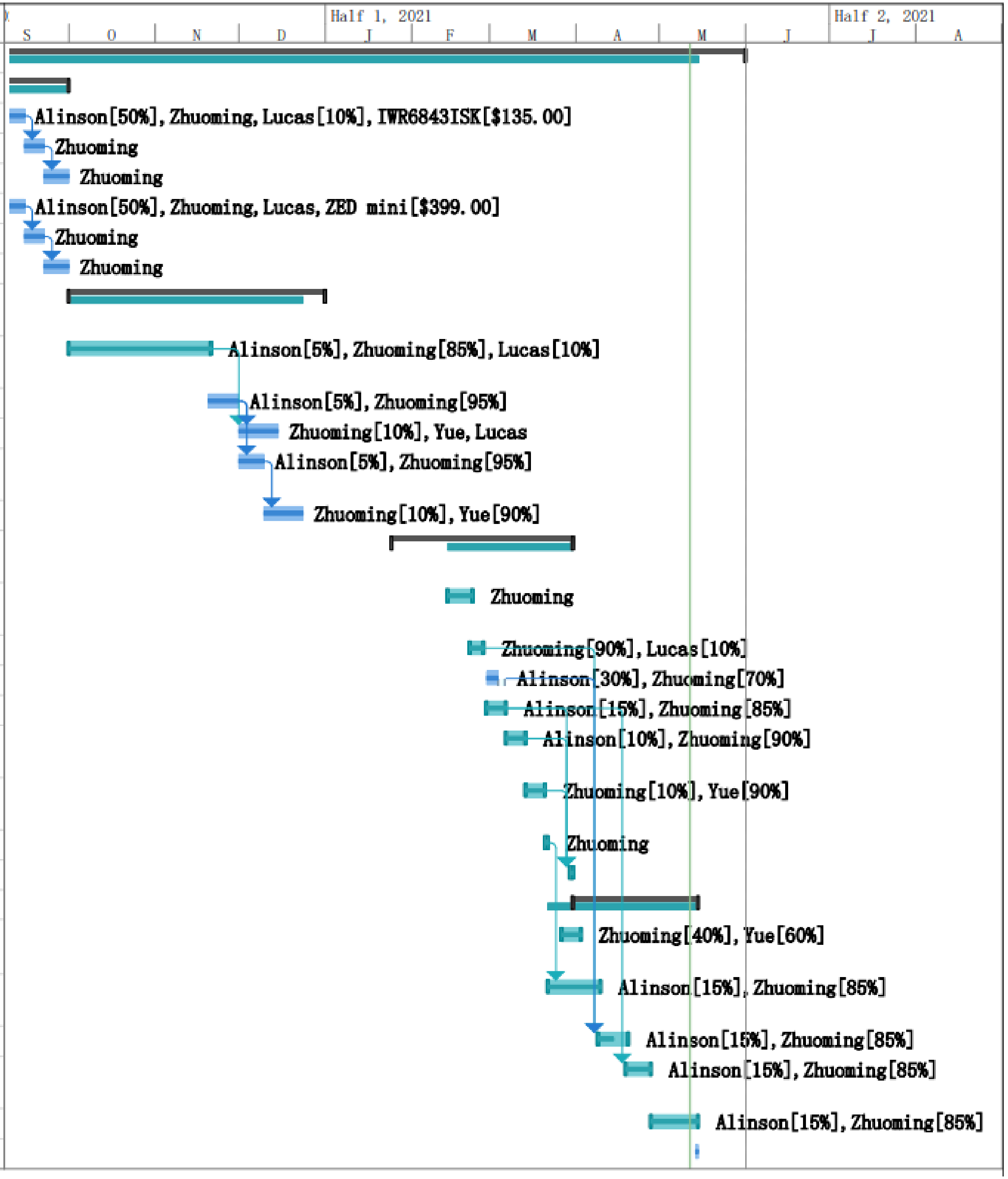
Alinson Sanquintin(Junior)

Team Introduction

- Technical Manager/ Customer Mentor:
  - Dr. Honggang Zhang
- Basic team members:
  - Zhuoming Huang
    - Collects and synthesizes 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.
- External team members:
  - Yue Sun
    - Builds Neural Networks to train AI models and generate 3D radar intensity maps/2D depth images.
  - Lucas Lomba
    - Helps with PCB design and UAV development
- Communication Plan
  - Weekly meetings: Zoom
  - File sharing: GitHub, Google Drive
  - Project management: MS Project

Project Management

ID	% Work Complete	Task Name	Duration	Start	Finish
1	**99%**	**Protable 3D Mapping System Desig**	**194 days**	**Tue 9/8/20**	**Mon 5/31/21**
2	**100%**	**Research**	**17 days**	**Tue 9/8/20**	**Wed 9/30/20**
3	100%	Reasech mmWave radars	5 days	Tue 9/8/20	Mon 9/14/20
4	100%	Radar configuration	5 days	Tue 9/15/20	Mon 9/21/20
5	100%	Test radar data collecting	7 days	Tue 9/22/20	Wed 9/30/20
6	100%	Reasech 3D camera	5 days	Tue 9/8/20	Mon 9/14/20
7	100%	Camera configuration	5 days	Tue 9/15/20	Mon 9/21/20
8	100%	Test camera data collecting	7 days	Tue 9/22/20	Wed 9/30/20
9	**100%**	**SAR Experiments and Neural Newwork Training**	**68 days**	**Thu 10/1/20**	**Thu 12/31/20**
10	100%	Collect, analyze and process data	39 days	Thu 10/1/20	Fri 11/20/20
11	100%	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	100%	Generate 3D intensity images	7 days	Tue 12/1/20	Wed 12/9/20
14	100%	AI model training (3D)	10 days	Thu 12/10/20	Wed 12/23/20
15	**100%**	**System verification and UAV development**	**48 days**	**Mon 1/25/21**	**Tue 3/30/21**
16	100%	3D printing 2D sliding mechanism 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	100%	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	100%	Design Validation	1 day	Tue 3/30/21	Tue 3/30/21
24	**96%**	**System Optimization and Tests**	**34 days**	**Wed 3/31/21**	**Fri 5/14/21**
25	100%	Scene reconstruciton w/ multiple depth images	6 days	Sat 3/27/21	Fri 4/2/21
26	100%	Drone stablization test (outdoor)	15 days	Mon 3/22/21	Fri 4/9/21
27	50%	Drone redesign	7 days	Fri 4/9/21	Mon 4/19/21
28	100%	Automation code for raw data collection	7 days	Mon 4/19/21	Tue 4/27/21
29	100%	System Optimization	14 days	Wed 4/28/21	Fri 5/14/21
30	100%	Final product ready	1 day	Fri 5/14/21	Fri 5/14/21



Problem Definition

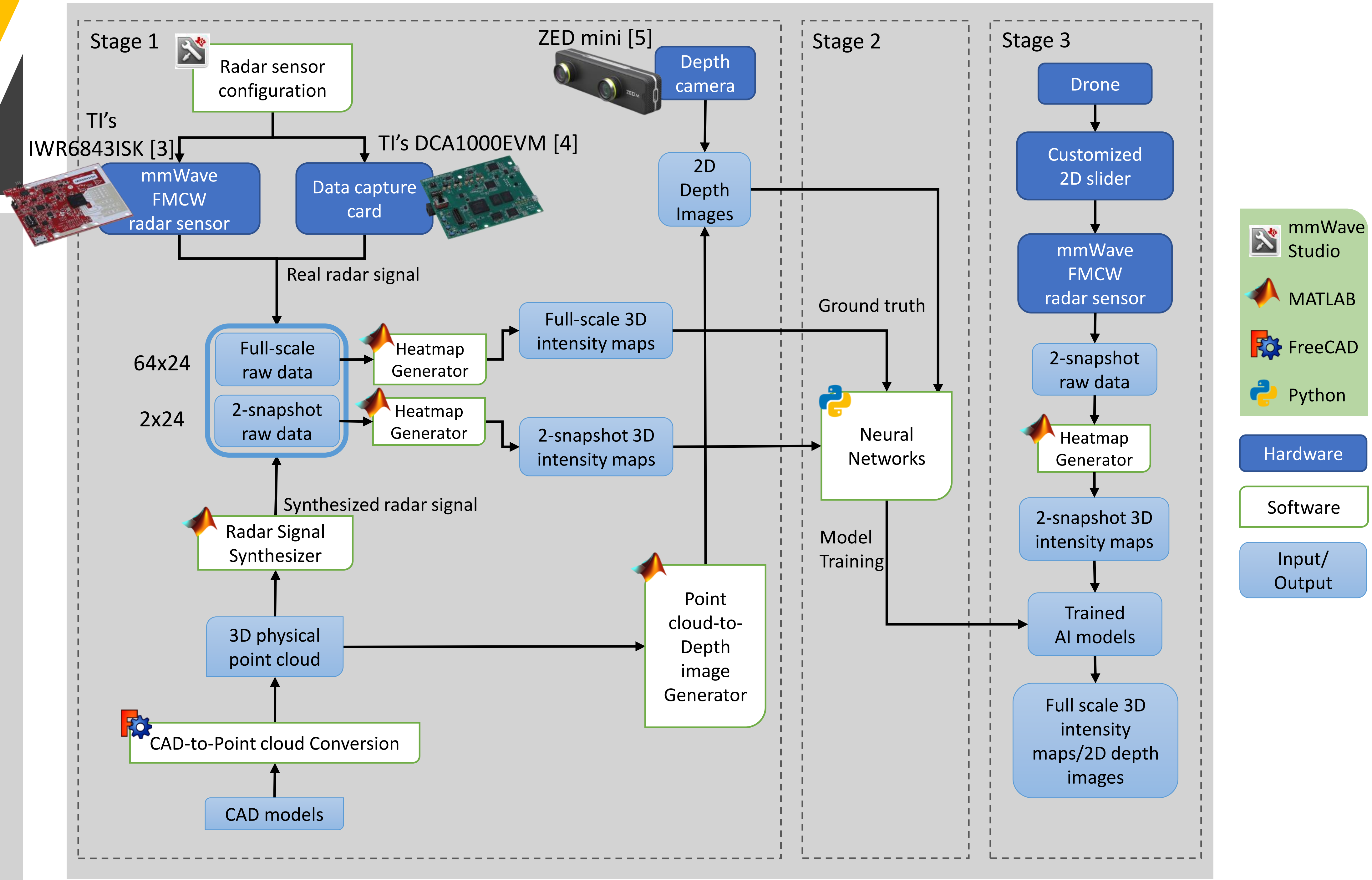
Motivations:

1. Unsafe to access unknown and high-risk areas (smoke, fog, low-visibility) for explorations or rescues [1][2]
2. Difficult to implement non-intrusive and privacy-preserving monitoring for public health and safety.
3. Managements of large-scale facilities need plenty of resource (time or labor) in traditional ways.
4. Application of mmWave radar sensors in autonomous driving.
5. UAV can move in a 3D space with high efficiency and flexibility.

Requirements:

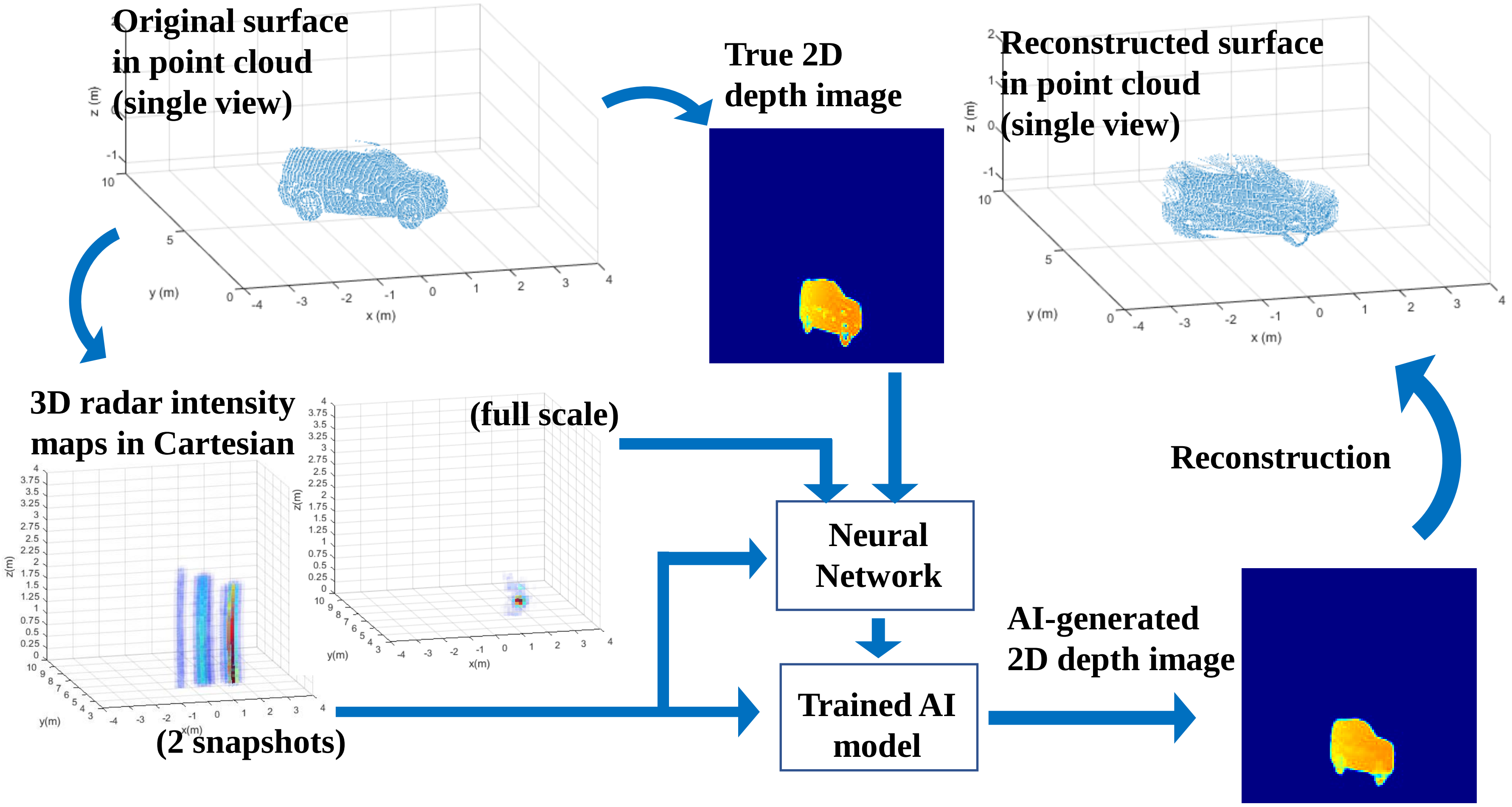
1. Capability to outline the shape of an object in a 3D space
2. Accurately estimates the position of an object
3. An UAV platform holding and moving the sensors
4. Low cost, and simple operations

System Architecture



System Architecture

Example using CAD car models [1]

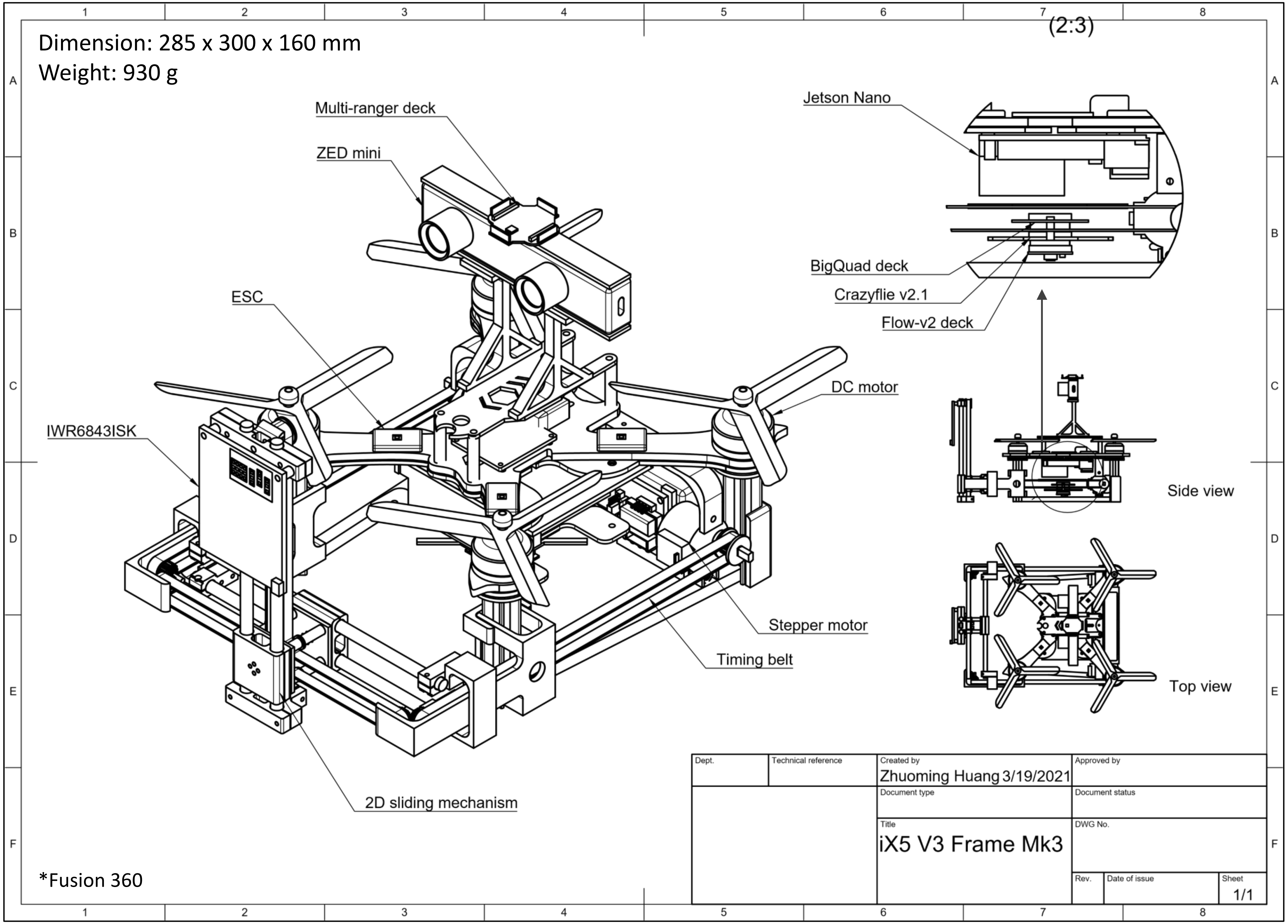


Pre-owned
Have purchased
Newly added
One time use
Plan to order

Final Budget

#	Item	Qty	Unit Price	Cost	Description	Status
1	IWR6843ISK	1	$135.00	$135.00	mmWave radar sensor	Purchased
2	ZED mini	1	$399.00	$399.00	3D depth camera	Purchased
3	T6x1-200mm Ball Screw Slide	4	$70.00	$280.00	For moving the radar sensor horizontally/ vertically in SAR experiments only	Purchased
4	Arduino Uno	1	$23.00	$23.00	Slider control	Purchased
5	Adafruit motor shield	1	$19.95	$19.95	Motor driver	Purchased
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	$99.00	$99.00	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
14	5V, 2.5A power cable	1	$10.00	$10.00		Purchased
	Total			*$1714.75*	*Data collecting + UAV sensing equipment*	
	Used budget			*$979.75*	*Out of the $1000 budget*	
	Final product estimated budget			***$965.80***	***UAV sensing equipment***	

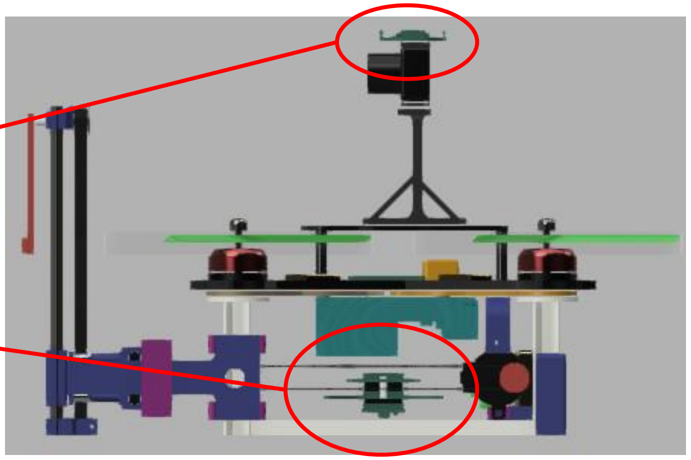
Drone Design



PCB Design

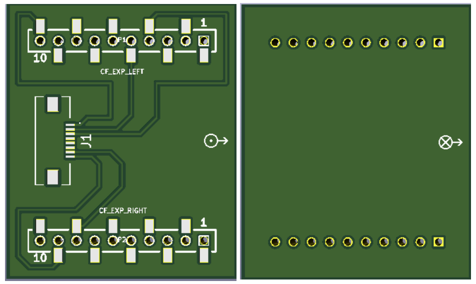
PCB deck connectors:

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.

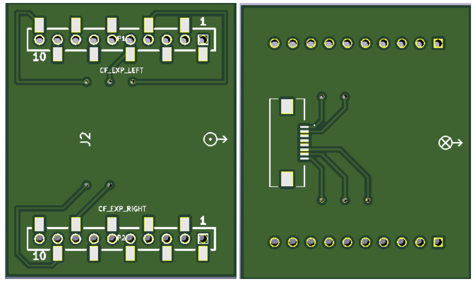


(Measures distance to ceiling and surrounding)

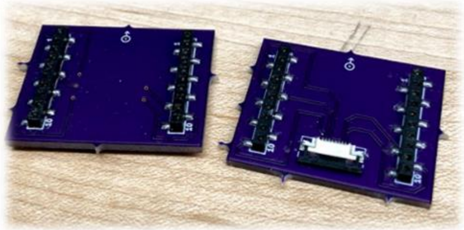
(Measures distance to the ground)

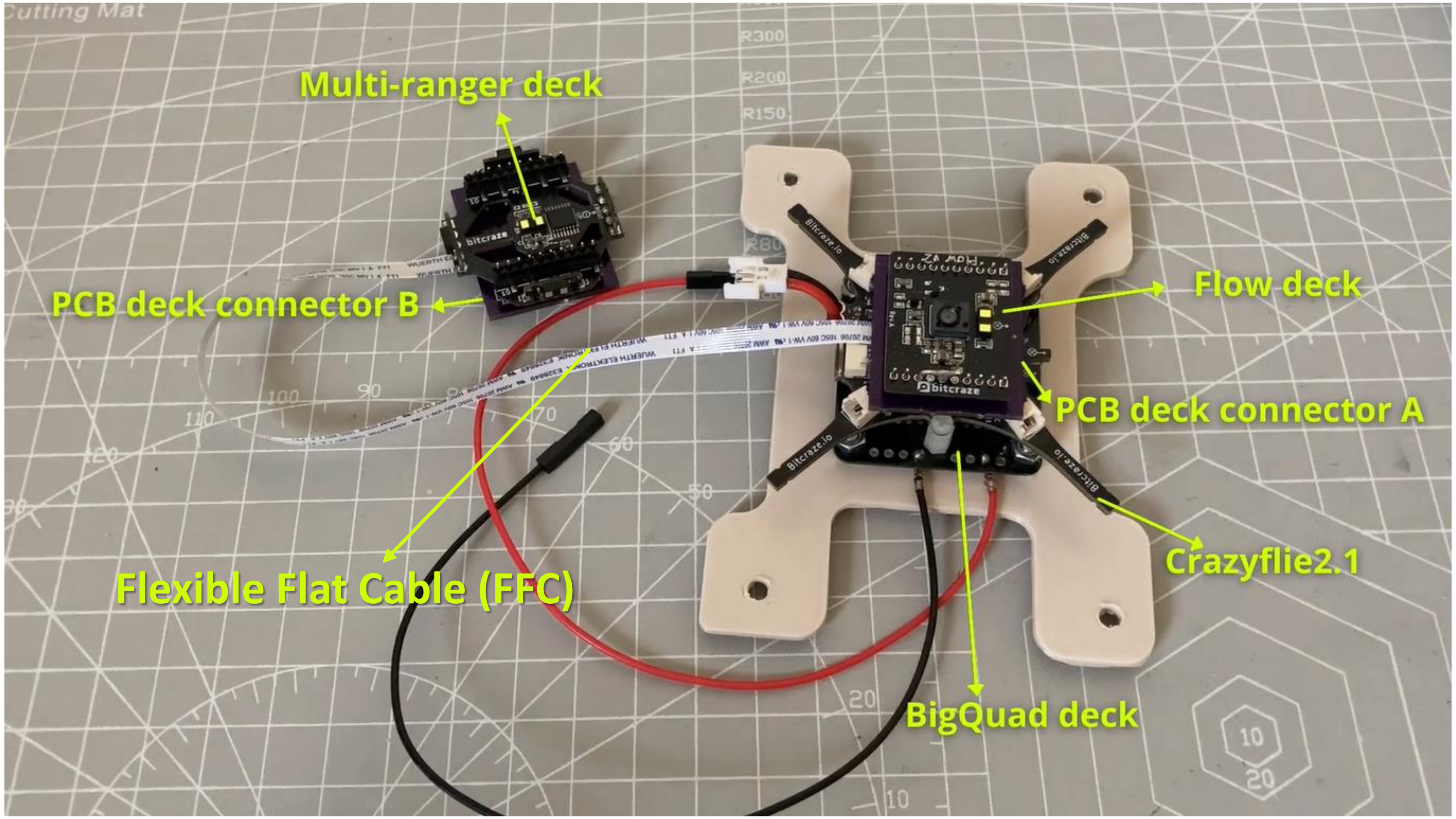


Deck connector A (front/back)



Deck connector B (front/back)



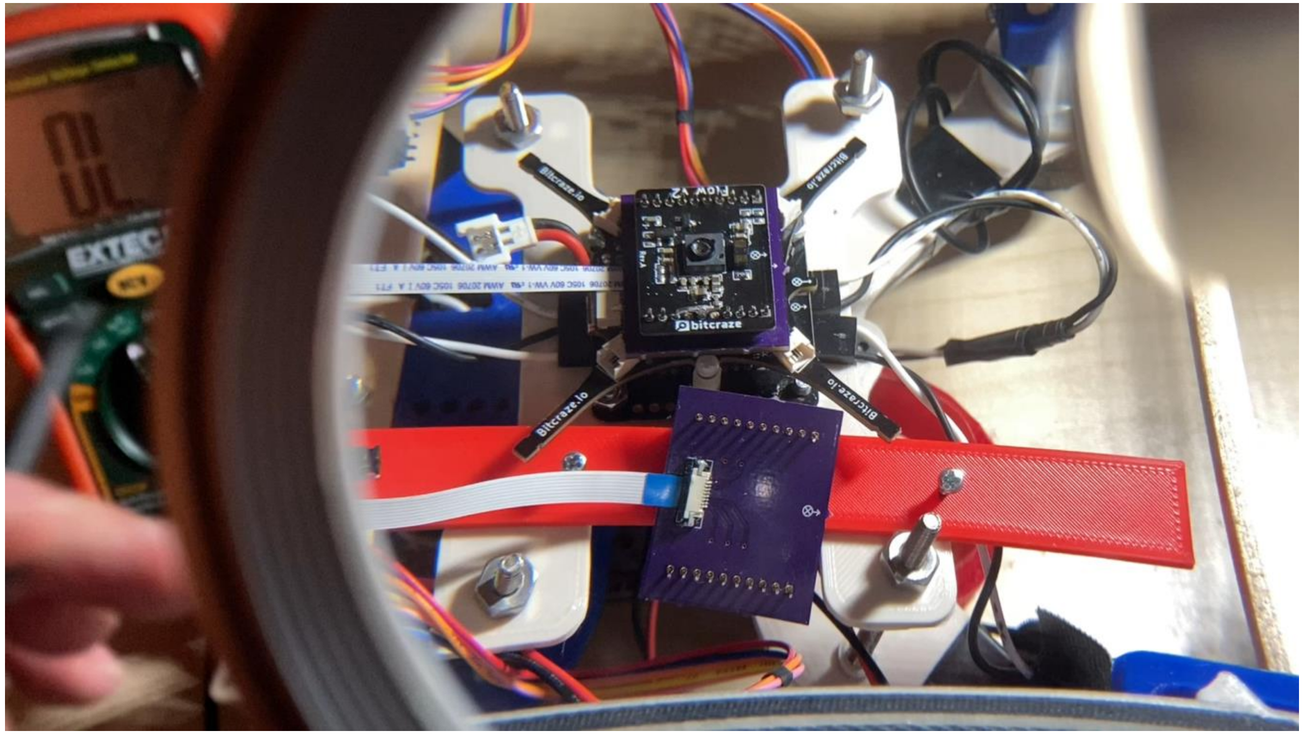


PCB Test

Connection test:
Check if FFC connectors are successfully soldered, and if pins are correctly connected.

Result:
Multi-ranger deck is recognized by Crazyflie PC client. No error was reported. All decks are fully functioning together.

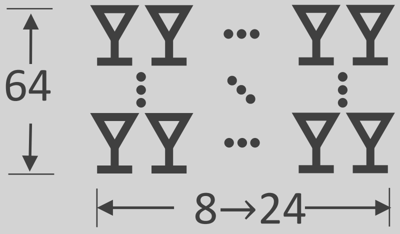
deck			
bcAIDeck	uint8_t	RO	0
bcBigQuad	uint8_t	RO	1
bcBuzzer	uint8_t	RO	0
bcCPPM	uint8_t	RO	0
bcDWM1000	uint8_t	RO	0
bcFlow	uint8_t	RO	0
bcFlow2	uint8_t	RO	1
bcGTGPS	uint8_t	RO	0
bcLedRing	uint8_t	RO	0
bcMultiranger	uint8_t	RO	1
bcOA	uint8_t	RO	0
bcUSD	uint8_t	RO	0
bcZRanger	uint8_t	RO	0
bcZRanger2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



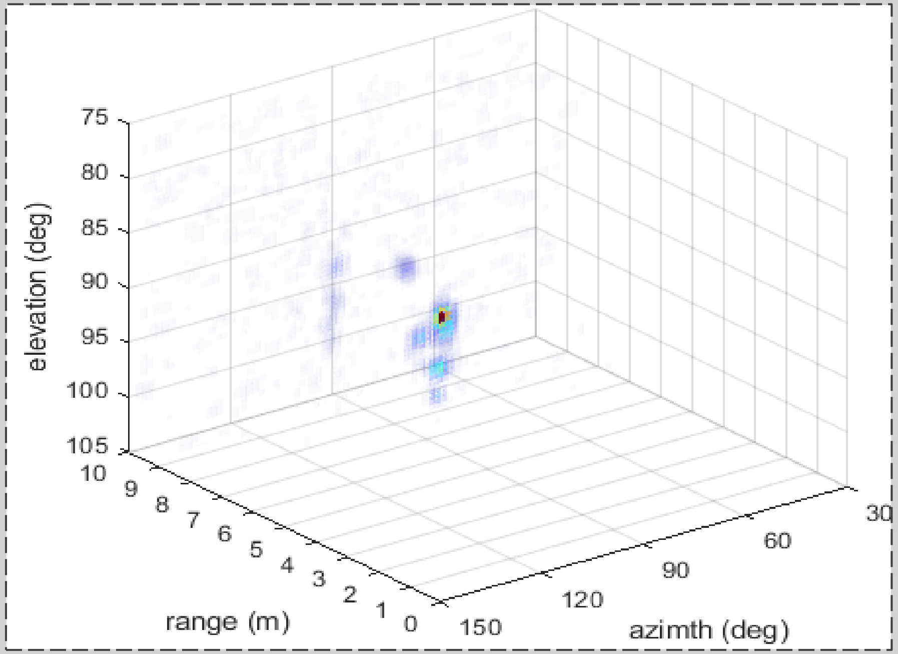
https://youtu.be/XsmHnefhABg

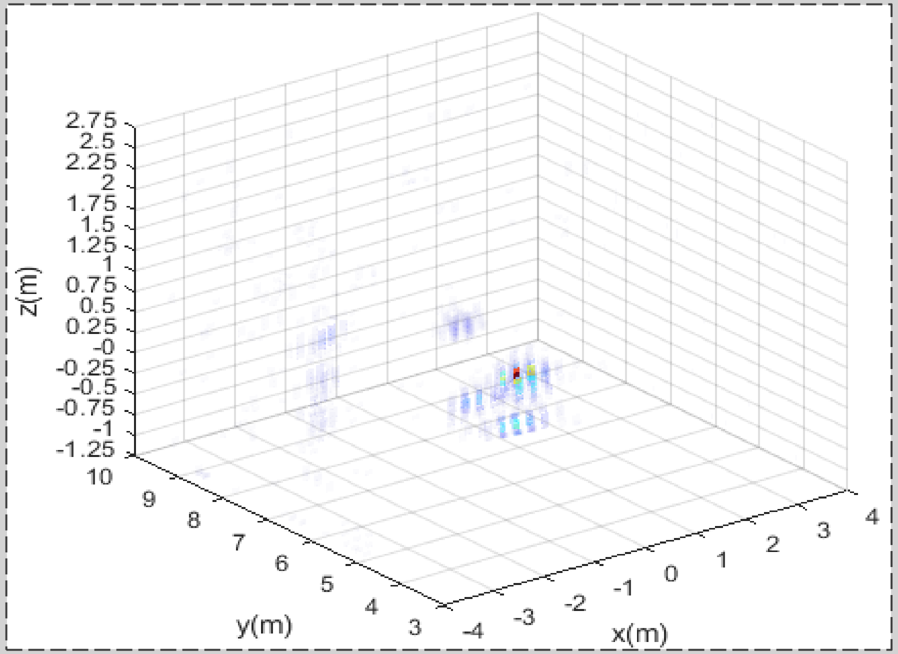
Design Improvements

- **Larger virtual antenna array size:**
  - **64X8 → 64x24**
  - Better resolution in azimuth: $\mathbf{15^\circ \rightarrow 5^\circ}$



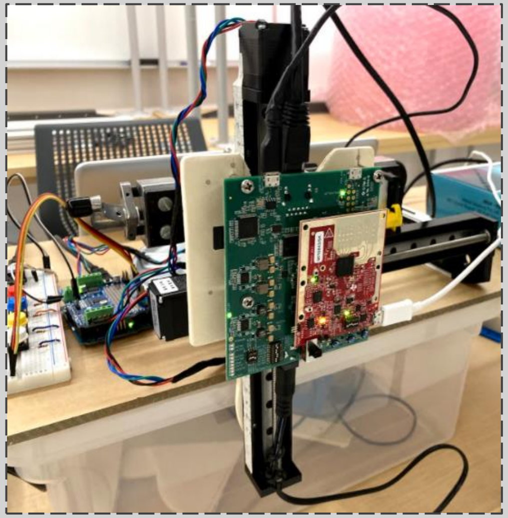
- **Synthesize data using CAD models for model training**
  - One real data sample takes up to **1 hours** for one scenario.
  - One synthesized data sample takes about **1.5 minutes** for one scenario.
  - Speed up data sample collecting process
- **Matching the coordinate systems of radar 3D intensity maps and camera 2D depth images**
  - **Spherical Coordinates → Cartesian Coordinates**

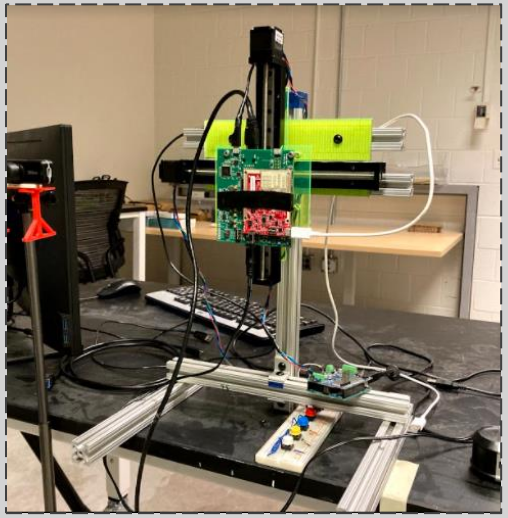




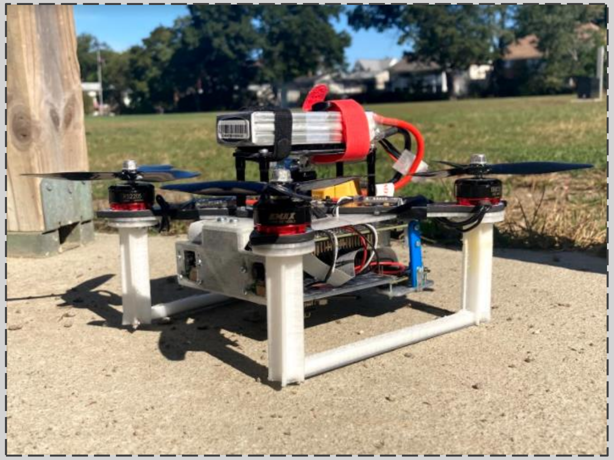
Design Improvements

- **2D sliding mechanism for raw data collection**
  - Manual control → Manual/Automatic
  - Stable and adjustable with T-slotted rails
- **UAV platforms**
  - **Mark-I:** Controlled by Crazyflie2.1 with BigQuad deck, added Flow-v2 deck for autonomous flights.
  - **Mark-II:** Added Jetson Nano and StereoPi camera, replaced legs.
  - **Mark-III:** Added 2D-sliding mechanism, TI's IWR6843ISK mmWave radar sensor, multi-ranger deck, replaced StereoPi with ZED mini depth camera.

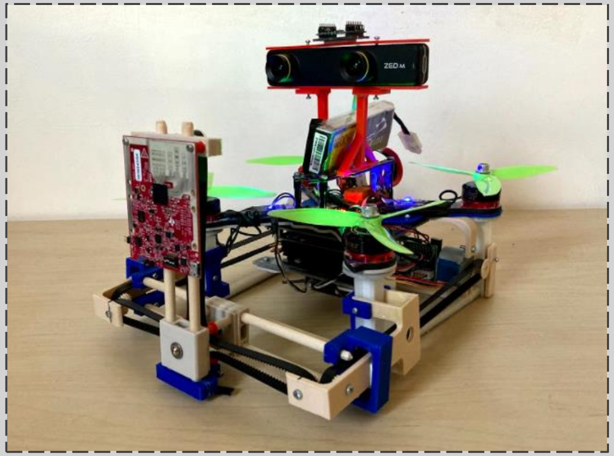




Mark I (06/2020)



Mark II (08/2020)



Mark III (Developing)

Ethical Consideration

- **Privacy Preserving**
  - Ask for permission if private properties are involved.
  - Keep camera off when it is not necessary, or when people feel uncomfortable in front of it.

- **Safety Standard**
  - UAV operators must wear protections (safety glasses, cut-resistance gloves)
  - Check conditions of motors, propellers, and battery before launching the UAV
  - Drop-in net covering the space for flight tests

Validation
– Depth Camera

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.

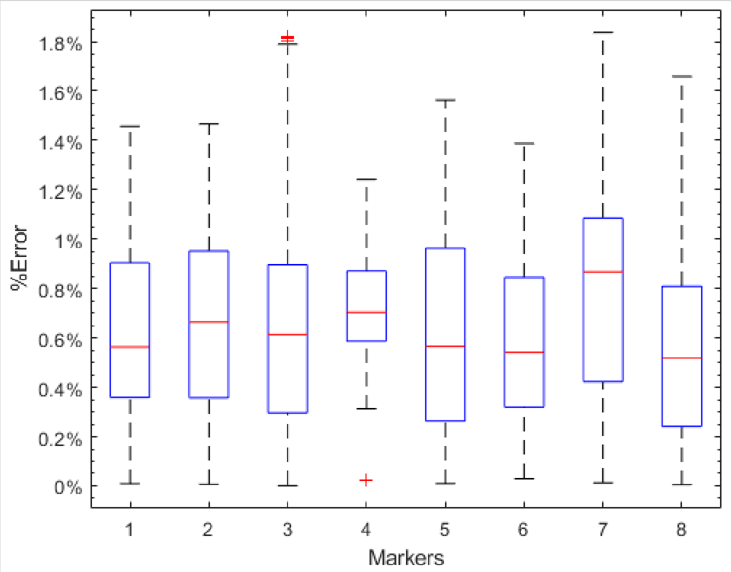
OptiTrack:
A set of fixed optical camera sensors that can provide accurate measurements with positional error < 0.3mm, and rotational error < 0.05°

*Thank Prof. Rahaim for his OptiTrack system

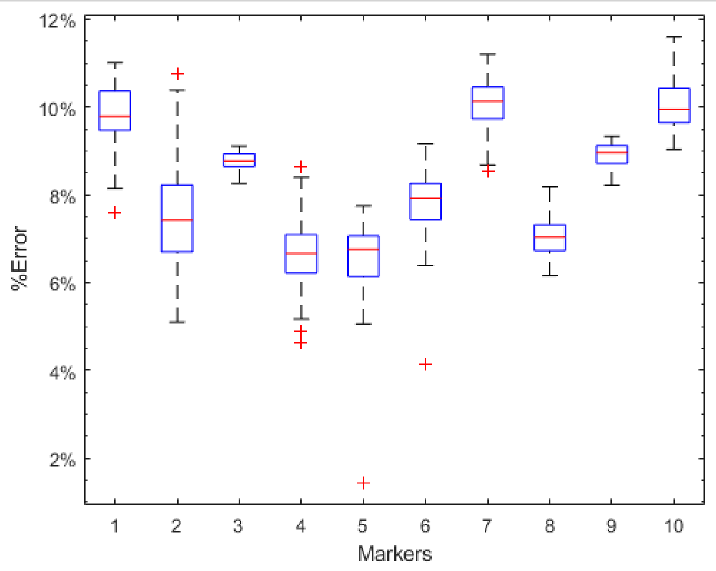
Validation Data
– Depth Camera

Accuracy in distance measurements

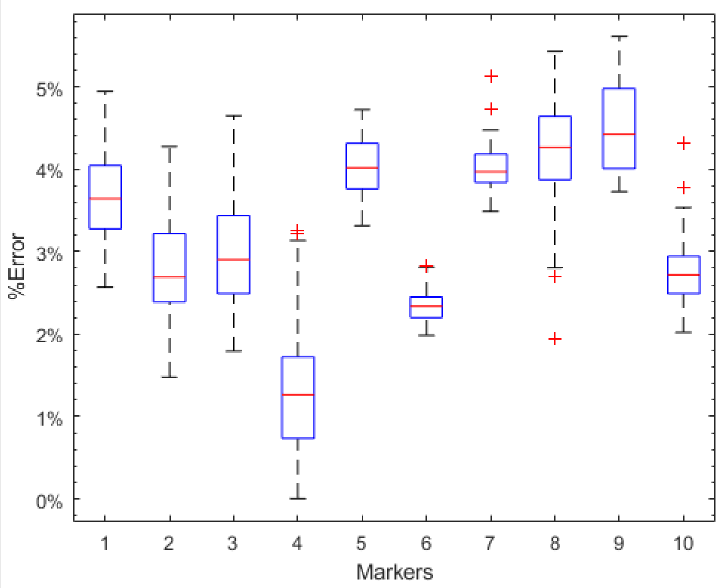
1. High brightness – High contrast



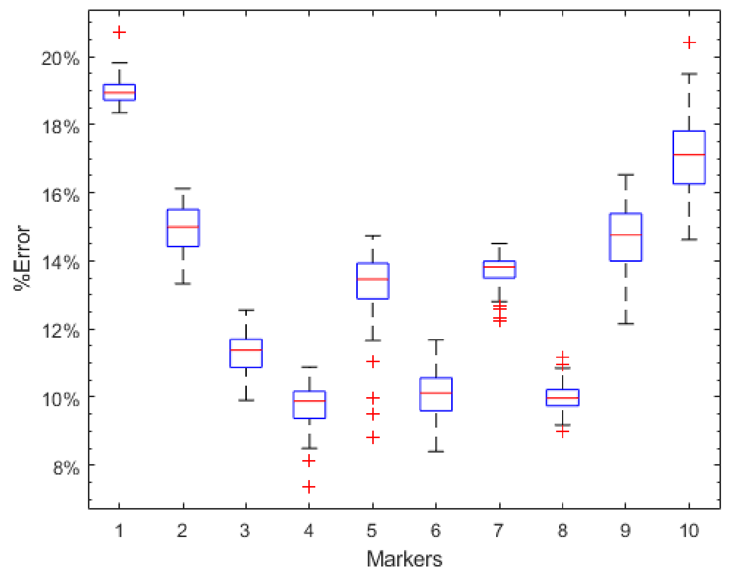
2. High brightness – Low contrast



3. Low brightness – High contrast



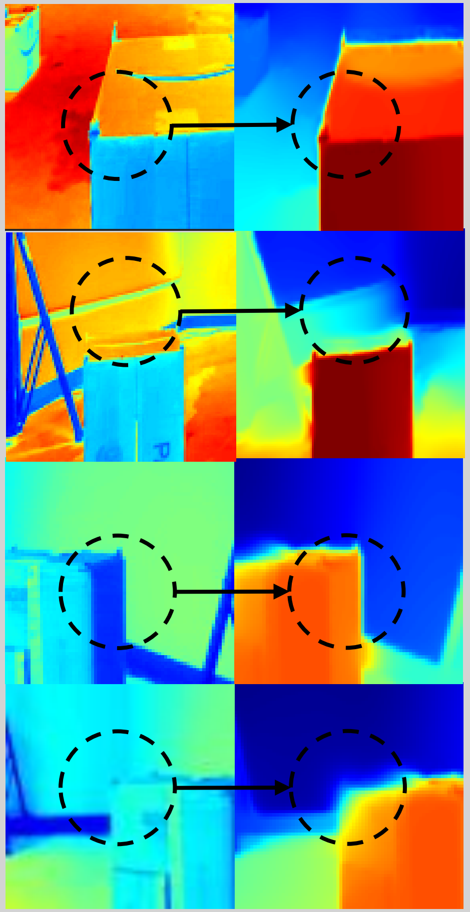
4. Low brightness – Low contrast



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

Brightness images   Depth images

1.
2.
3.
4.



Validation

–mmWave Radar

Test 2: mmWave Radar sensor

Reference: OptiTrack

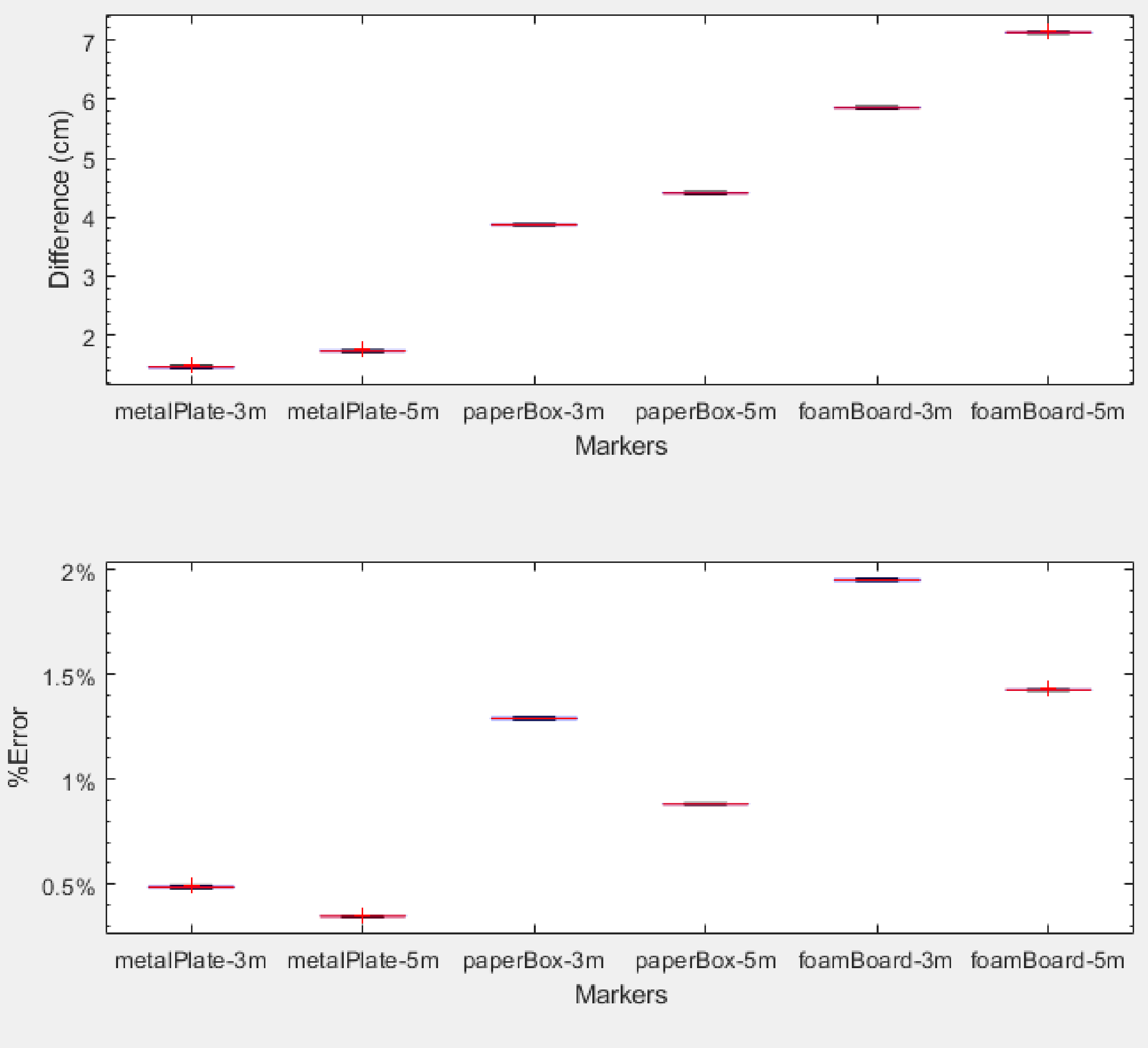
In a room, place objects at some distance. For each object, place markers at the four corners of the surface facing towards the radar sensor. Measure and compare the distance from radar sensor to that surface over 100 frames of video/chirps of signal.

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

*Thank Prof. Rahaim for his OptiTrack system

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:

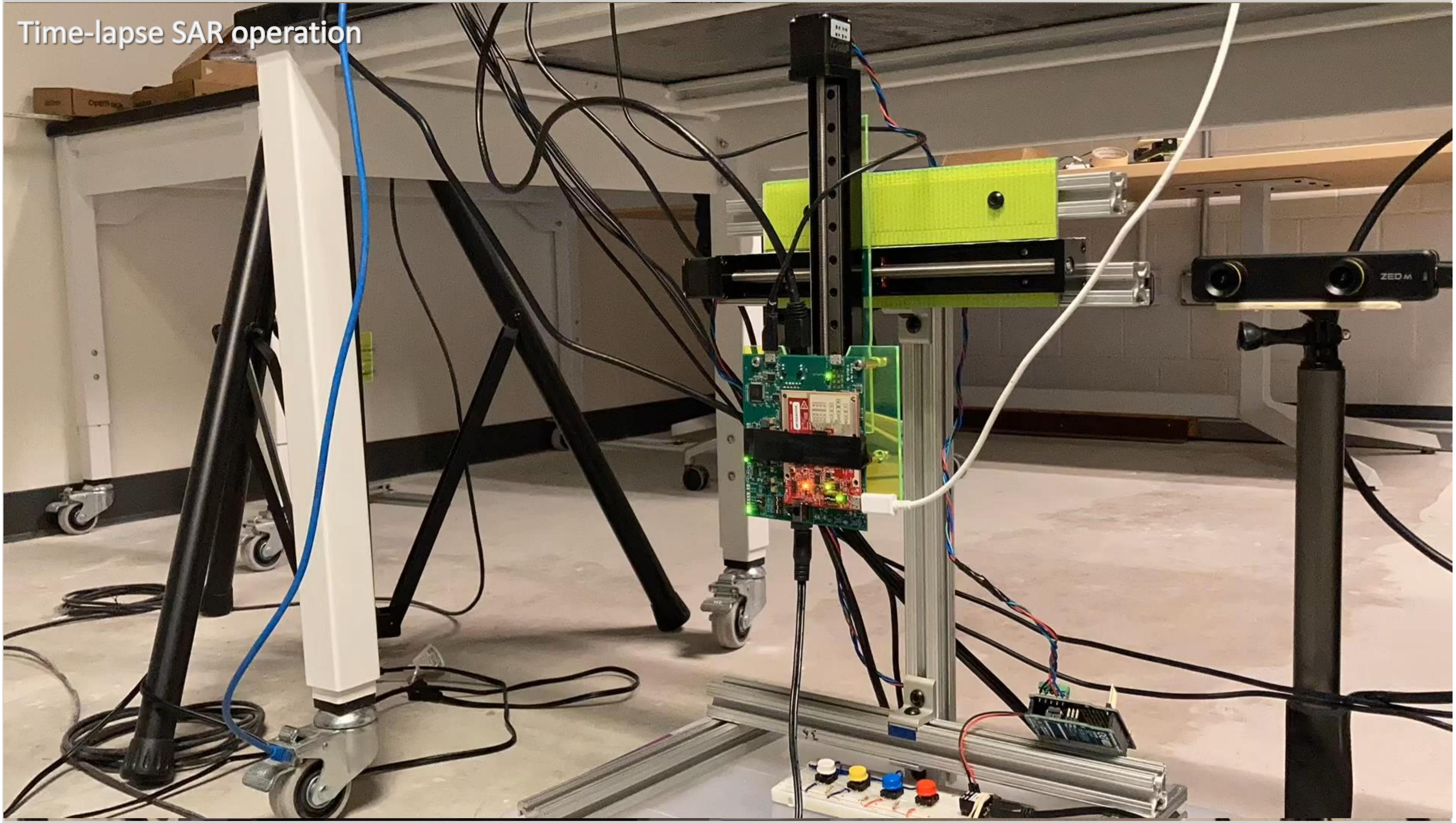
- Metal plate: strong reflection
- Paper box: weak reflection
- Foam board: multi-path reflection

	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 & Operation



https://youtu.be/aZofhSfoh1s

https://youtu.be/5lDimbV1rhI

Validation Data – Neural Network

Test 3: Neural Network

- Synthesized data with CAD car models [1]
- 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 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.

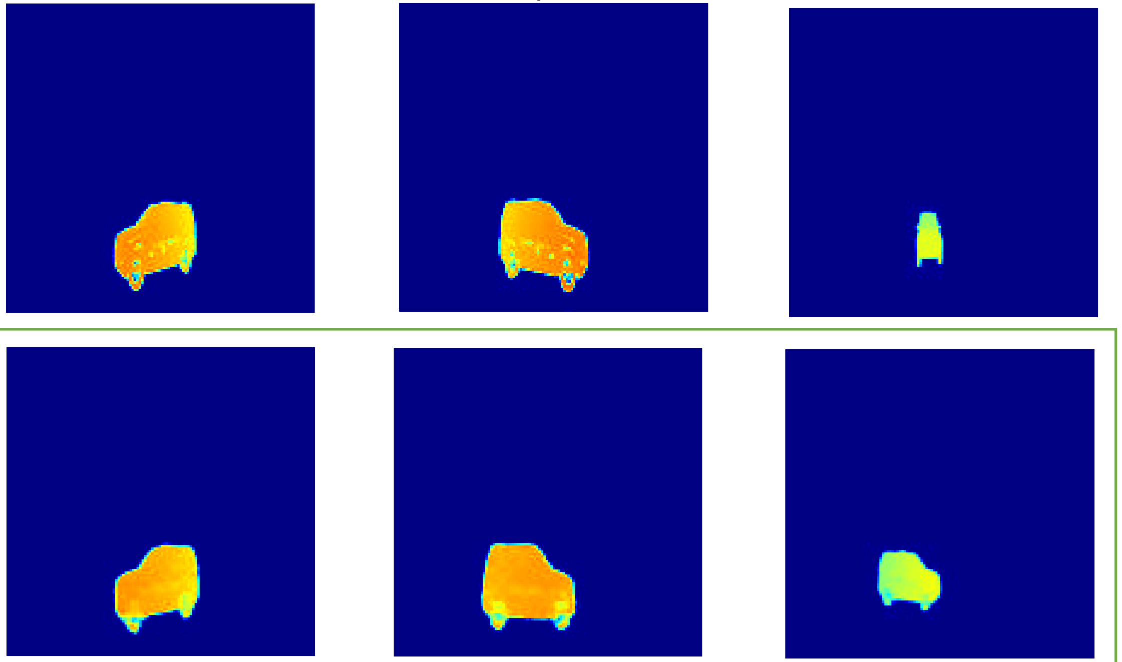
Tested workflow: 2-snapshot 3D radar intensity map → 2D depth image

Examples of results:

Good | Acceptable | Bad

True depth images (synthesized from CAD car models[1])

AI-generated depth images



Matched in color, size and orientation | Similar in color, size and orientation | Wrong size and orientation

Train	**2475**	
Verify	**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
– Neural Network

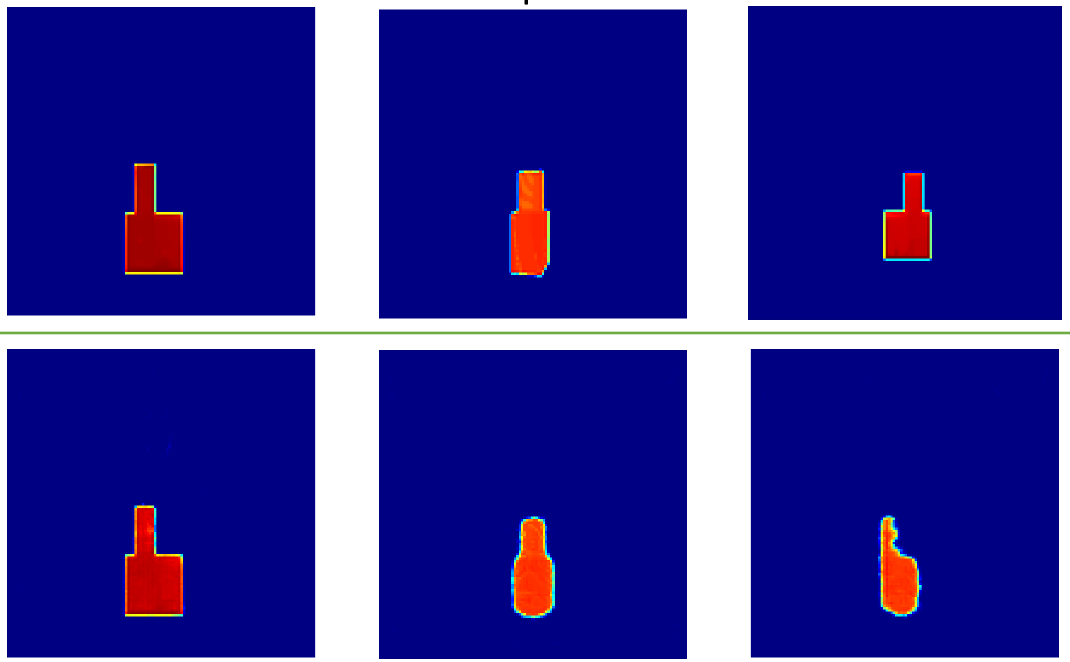
Test 3: Neural Network

- L-shape boxes
- Reference: Real + synthesized 2D depth images
- 400 real data samples + 2400 synthesized data samples
- Used 2500 samples for training, 300 for verification

Tested workflow: 2-snapshot 3D radar intensity map → 2D depth image

Examples of results:

	Good	Acceptable	Bad
True depth images			
AI-generated depth images			
	Matched in color, size and orientation	Similar in color, size and orientation	Wrong color, size and orientation



Train	**2500**		
Verify	**300**		
Good	125	42%	
Acceptable	106		77%
Bad	69		

Generator losses	
G_GAN:	0.693
G_L1(*1000):	26.244
G_Lp(*20):	21.651

Discriminator losses	
D_real:	0.408
D_fake:	0.694

Validation Data – Drone

Test 4: Power supply of Drone

Run the motors under different settings of throttle, record the voltage of battery every 5 minutes.

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

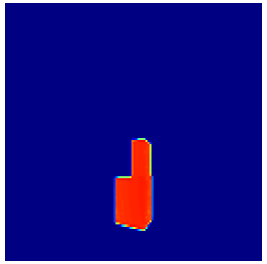
Time (min)	Battery Voltage (V)
0	12.51
5	12.40
10	**11.99**
15	11.16
20	10.95

100% Throttle

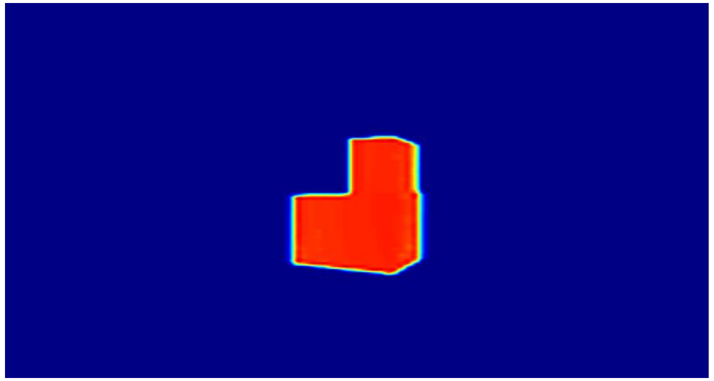
Time (min)	Battery Voltage (V)
0	12.60
5	11.73
10	**11.34**
15	11.13
20	9.65

Sufficient for collecting one data sample (2 snapshots, single point of view), but insufficient for more data samples or more points of view.

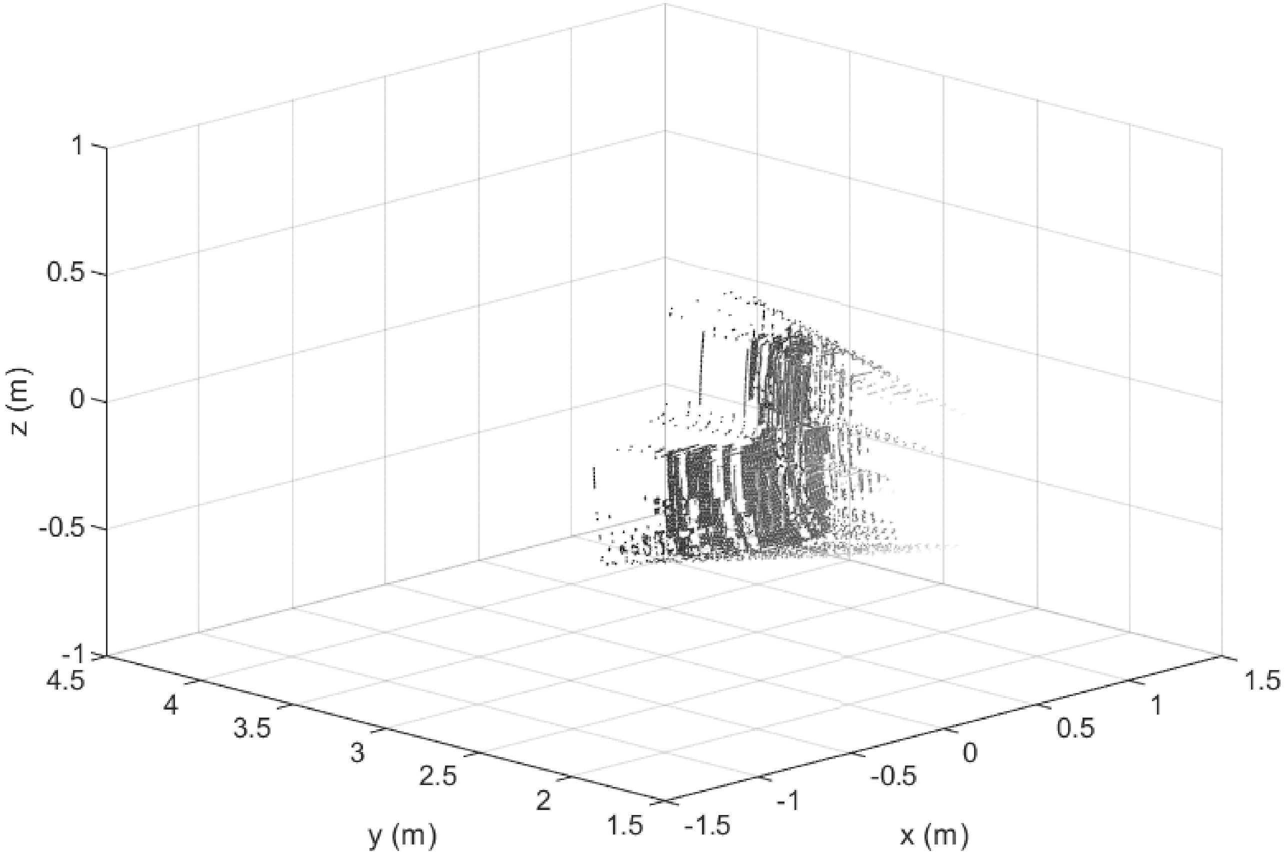
Example Result



128x128
(size for model training)



1280x720
(original size)



Based on ZED mini configuration (pixel size, focal length, etc.)

Deliverables

- A 3D-object reconstruction system
  - Goal: Generates depth images from sparse raw mmWave radar data.
  - Data-collecting and 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 platform design
    - Drone with SAR mechanism holding and moving the radar sensor and depth camera (Fig. 2)

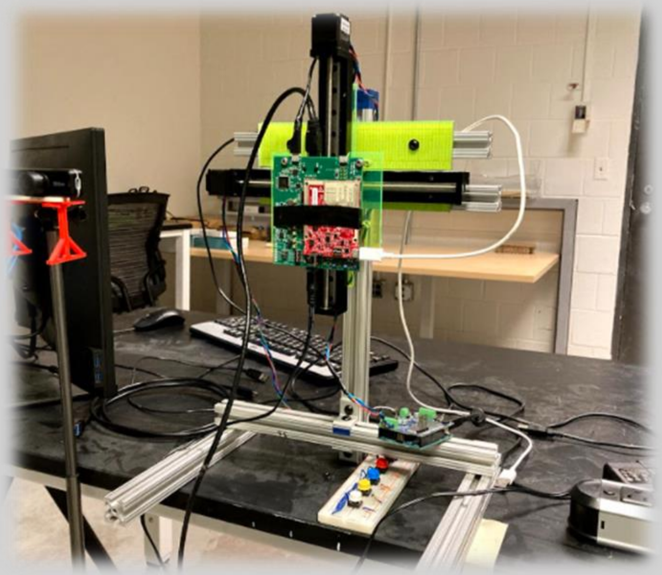


Fig. 1

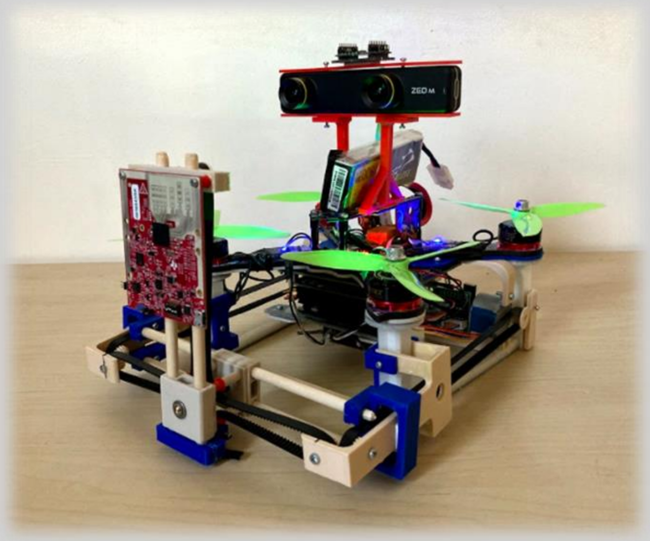


Fig. 2

Current Status & Future Work

- Higher resolution AI-generated depth images → more features for small objects
- Deep Neural Network for multiple-view 3D intensity maps/2D depth images
- 3D-space mapping and reconstruction
- Larger loads, longer flight time with bigger drone frame, more powerful motors, and higher capacity battery.
- Flight stabilization through better PID tuning and balancing

Acknowledgement and References

Yue Sun: Building Neural Networks

Dr. Honggang Zhang: Customer mentor and technical manager

Dr. Tomas Materdey: Teaching senior design courses

Dr. Michael B. Rahaim: Providing OptiTrack system

Andrew Davis: Supplying resources

Lucas E. Lomba: Helping with drone design

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Thank you

Question?