



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

Final Product Presentation

05/14/2021

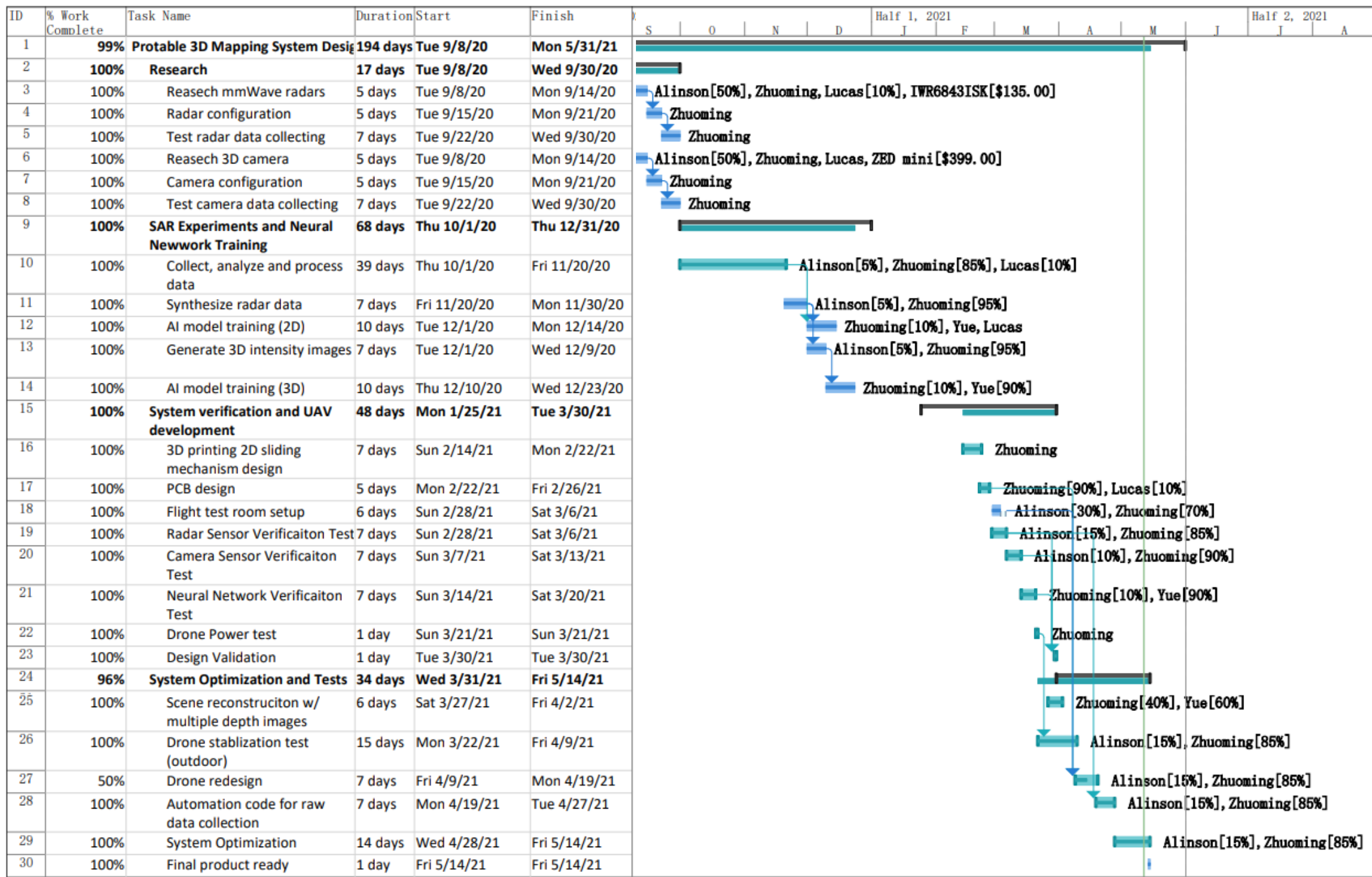
Team 4

Customer Mentor/Technical Manager:
Dr. Honggang Zhang

Zhuoming Huang(Senior)
Alinson Sanquintin(Junior)

- 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



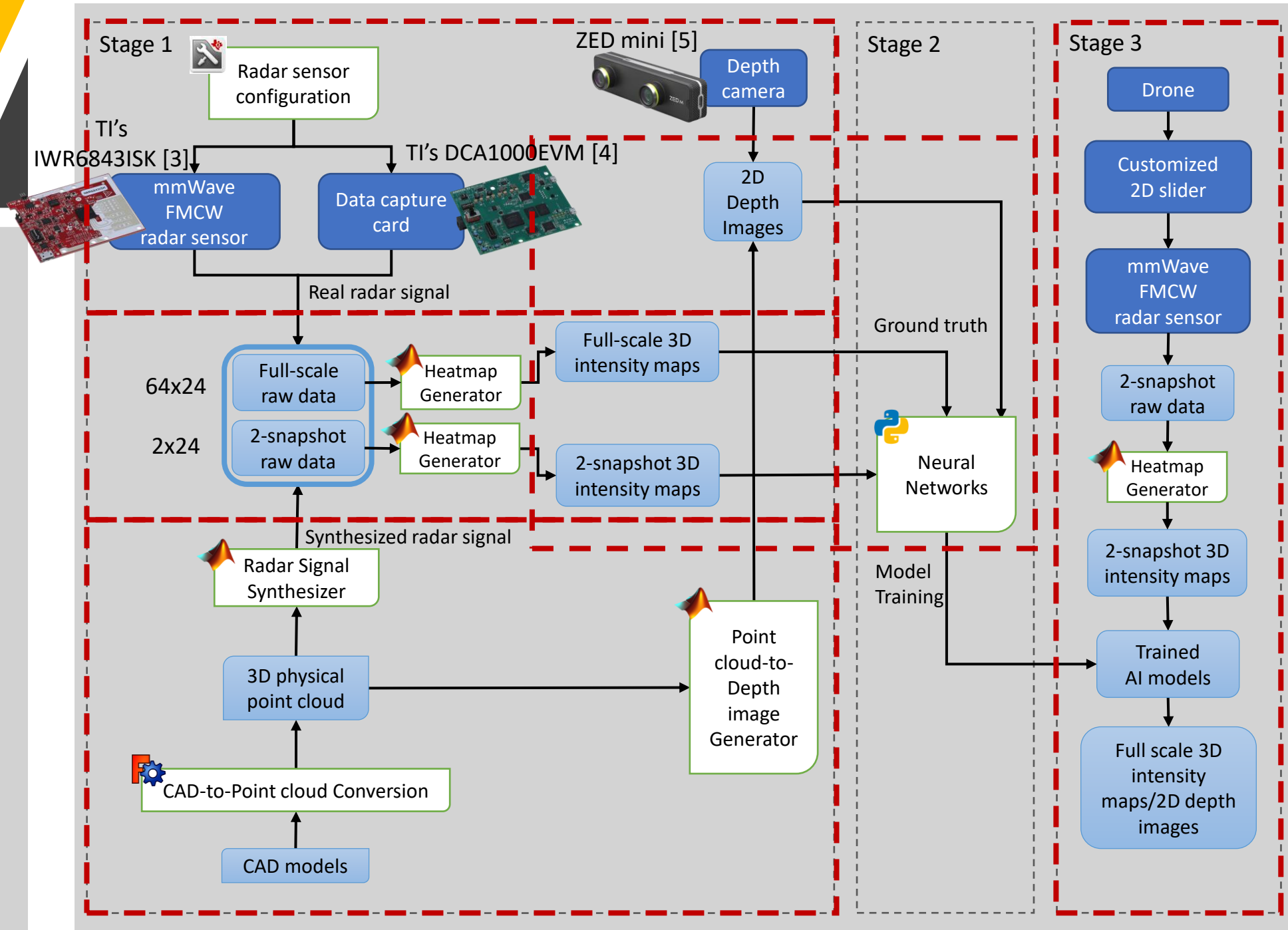
Motivations:

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



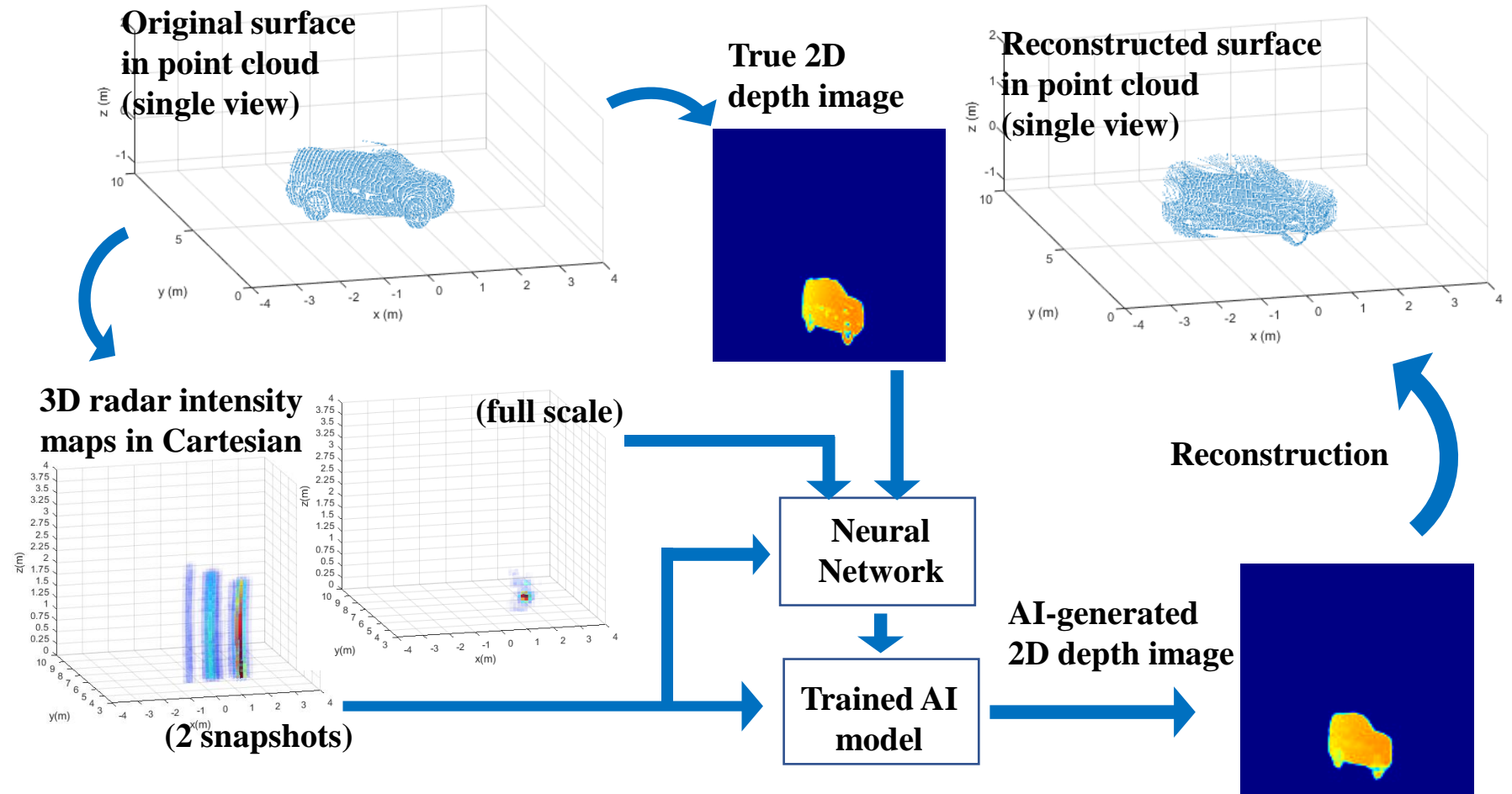
mmWave Studio
MATLAB
FreeCAD
Python

Hardware

Software

Input/
Output

Example using CAD car models [1]



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

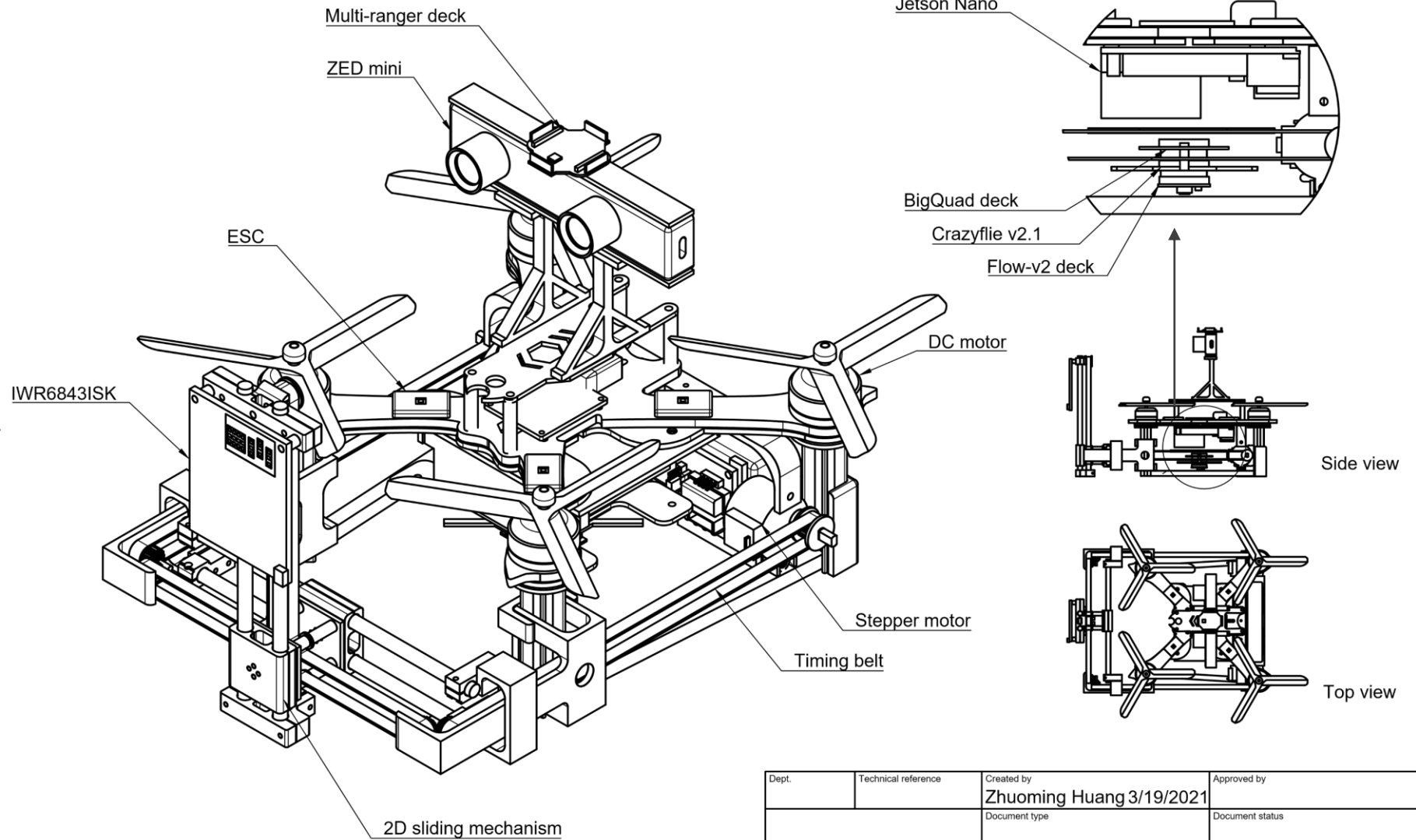
Final
Budget

#	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

Dimension: 285 x 300 x 160 mm

Weight: 930 g

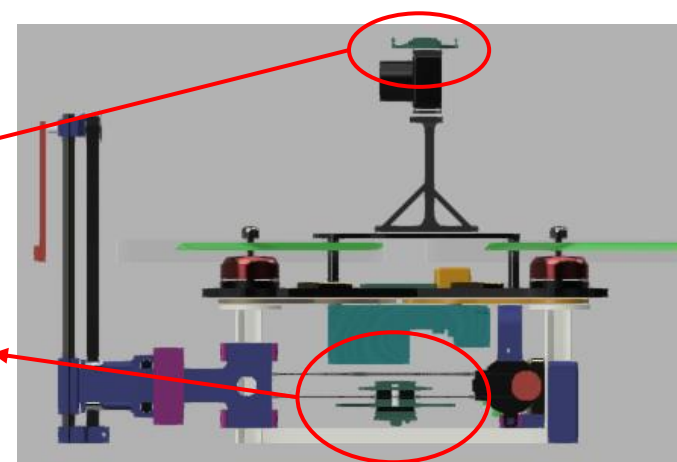


*Fusion 360

Dept.	Technical reference	Created by Zhuoming Huang 3/19/2021	Approved by	
		Document type	Document status	
		Title iX5 V3 Frame Mk3	DWG No.	
		Rev.	Date of issue	Sheet 1/1

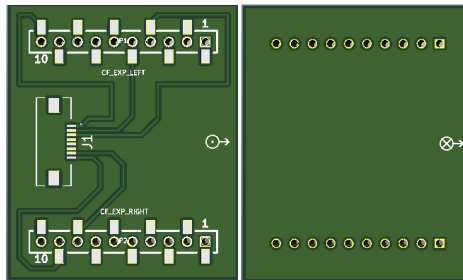
PCB deck connectors:

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.

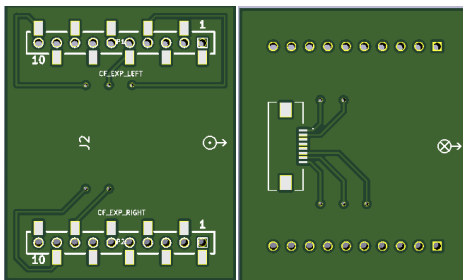


(Measures distance to ceiling and surrounding)

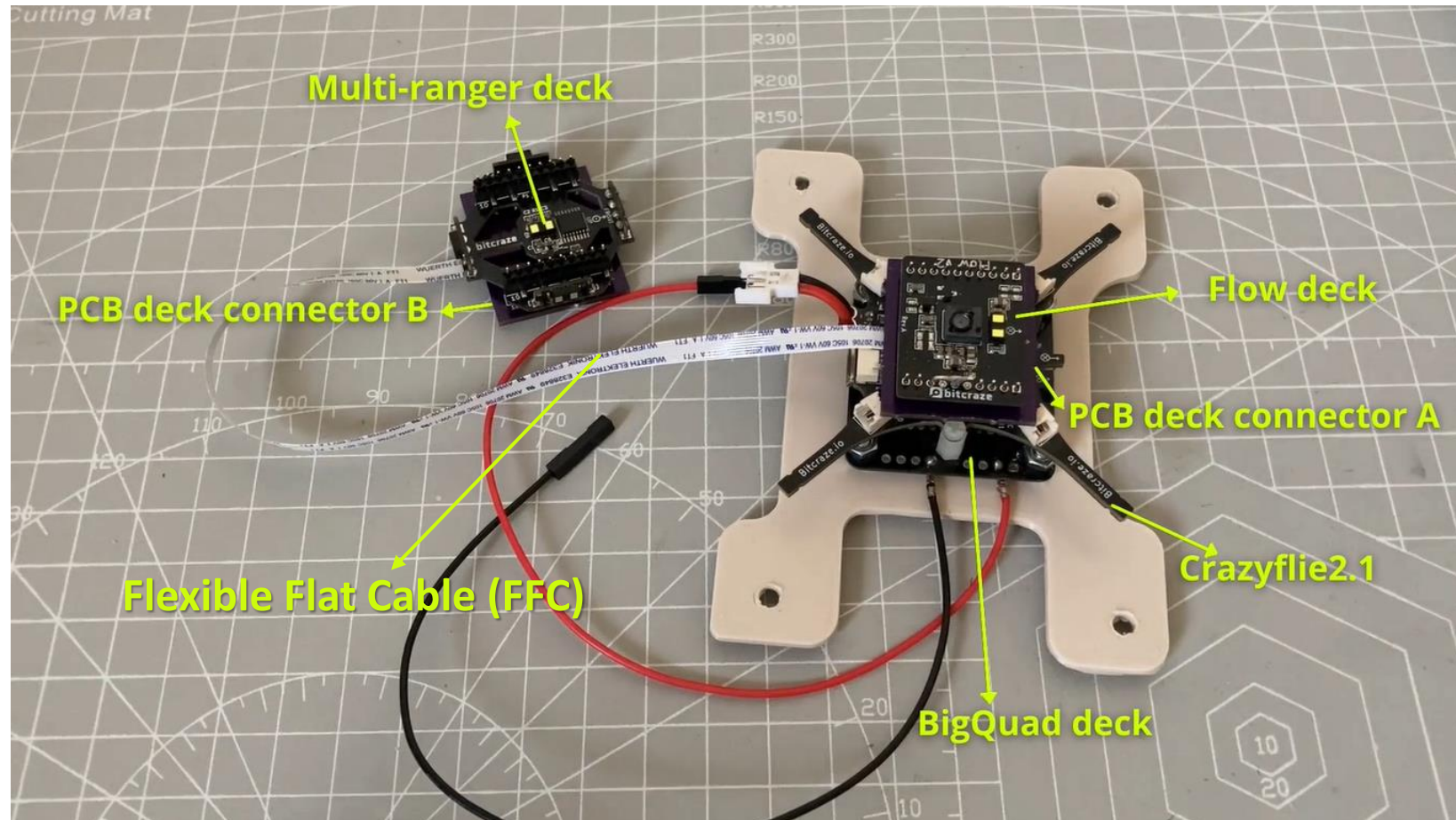
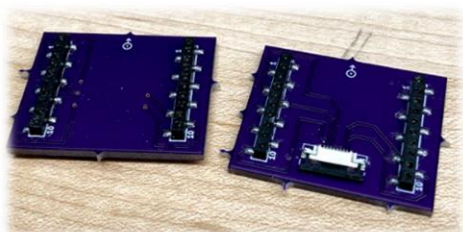
(Measures distance to the ground)



Deck connector A (front/back)



Deck connector B (front/back)



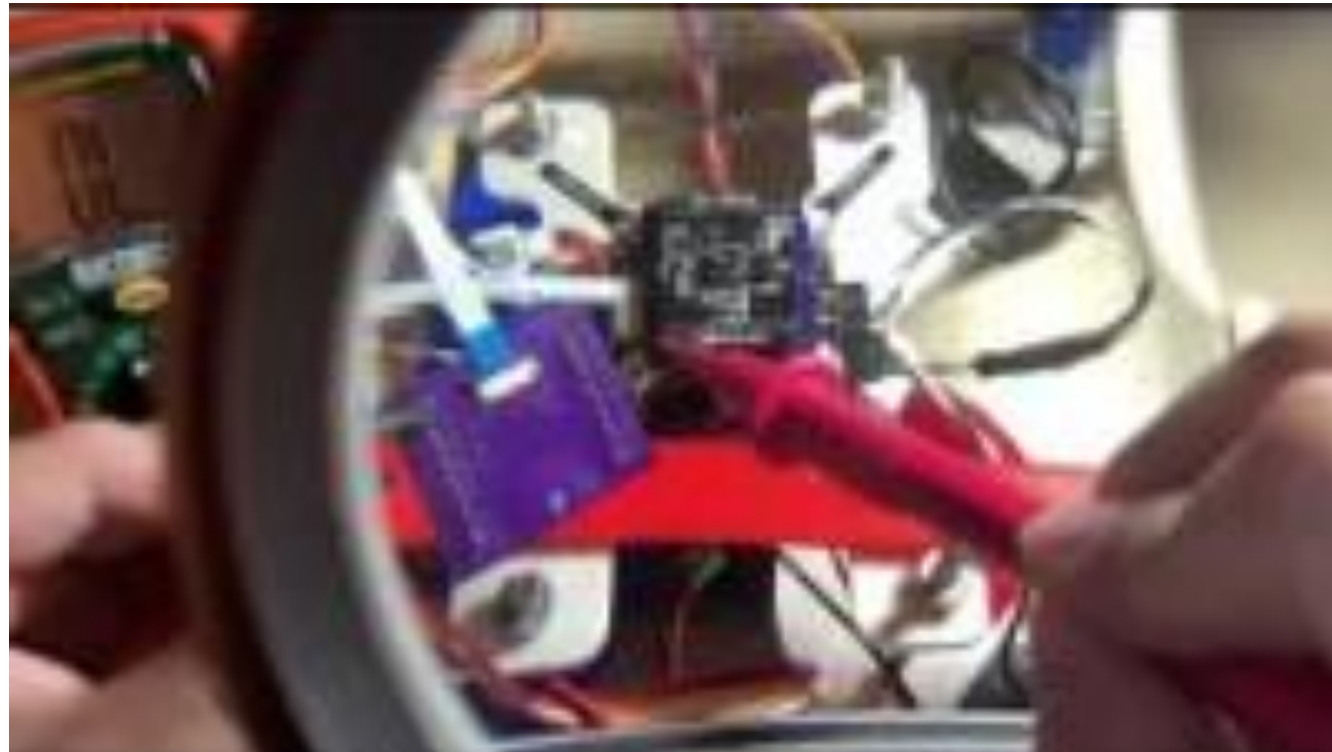
Connection test:

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

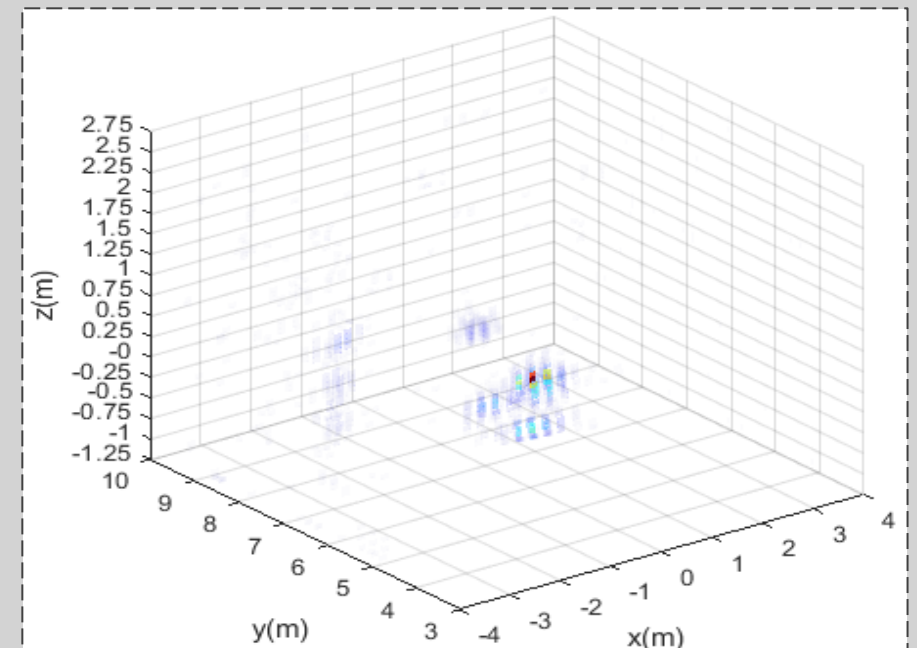
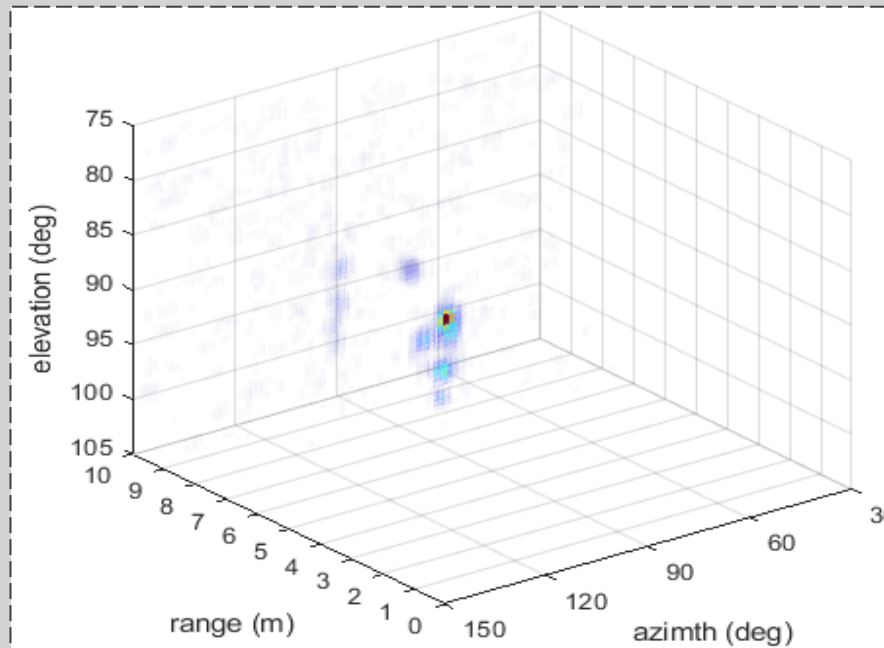
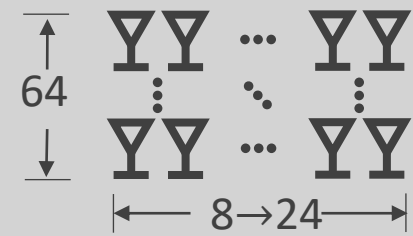
Result:

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

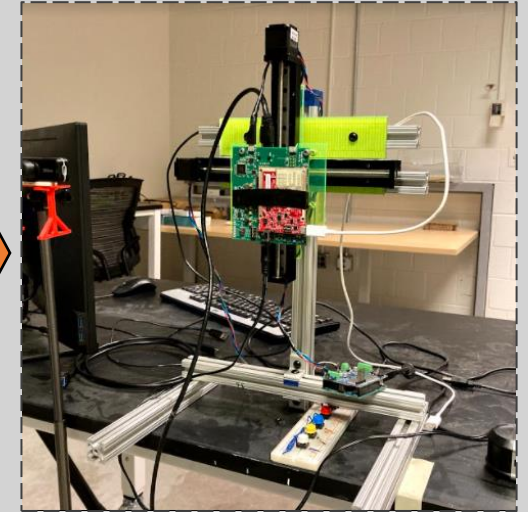
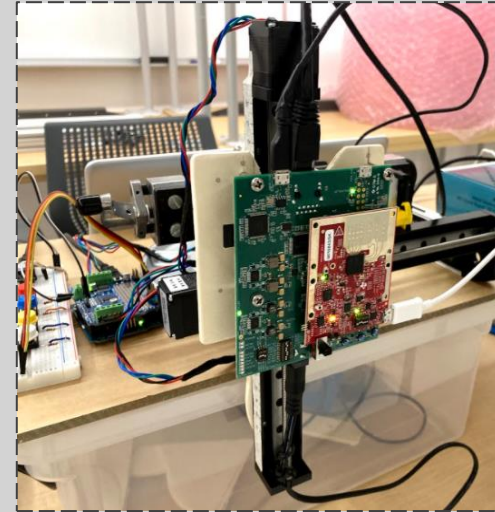
▼ deck				
bcAIDeck	uint8_t	RO		0
bcBigQuad	uint8_t	RO		1
bcBuzzer	uint8_t	RO		0
bcCPPM	uint8_t	RO		0
bcDWM1000	uint8_t	RO		0
bcFlow	uint8_t	RO		0
bcFlow2	uint8_t	RO		1
bcGTGPS	uint8_t	RO		0
bcLedRing	uint8_t	RO		0
bcMultiranger	uint8_t	RO		1
bcOA	uint8_t	RO		0
bcUSD	uint8_t	RO		0
bcZRanger	uint8_t	RO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



- **Larger virtual antenna array size:**
 - 64X8 → 64x24
 - Better resolution in azimuth: 15° → 5°
- **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



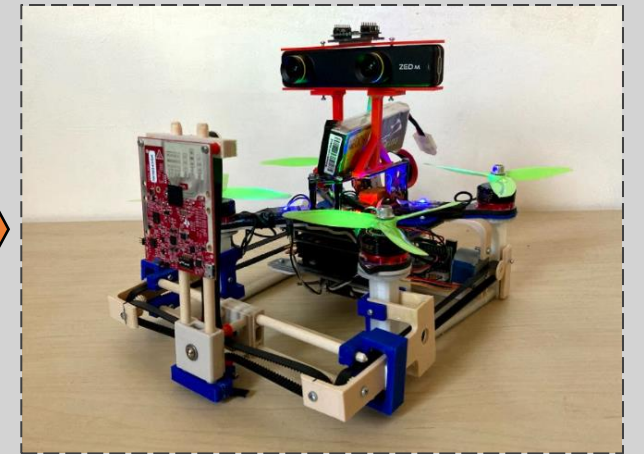
- **2D sliding mechanism for raw data collection**
 - Manual control → Manual/Automatic
 - Stable and adjustable with T-slotted rails
- **UAV platforms**
 - **Mark-I:** Controlled by Crazyflie2.1 with BigQuad deck, added Flow-v2 deck for autonomous flights.
 - **Mark-II:** Added Jetson Nano and StereoPi 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)

- **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



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:

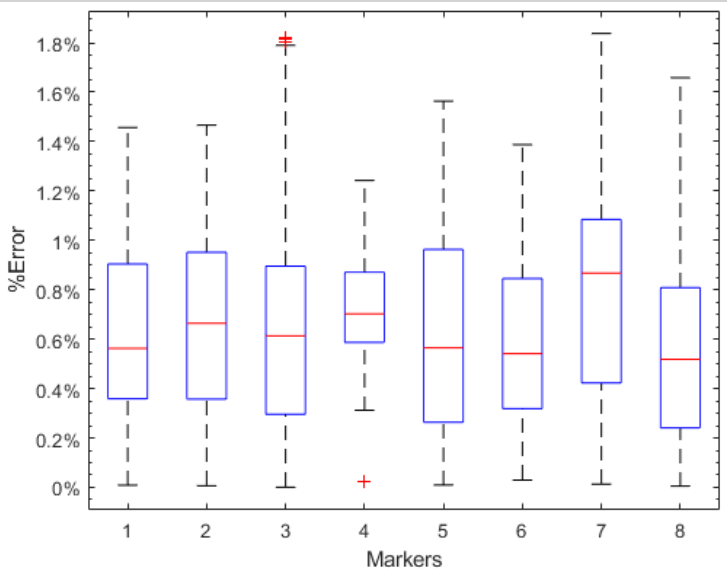
A set of fixed optical camera sensors that can provide accurate measurements with positional error $< 0.3\text{mm}$, and rotational error $< 0.05^\circ$

*Thank Prof. Rahaim for his OptiTrack system

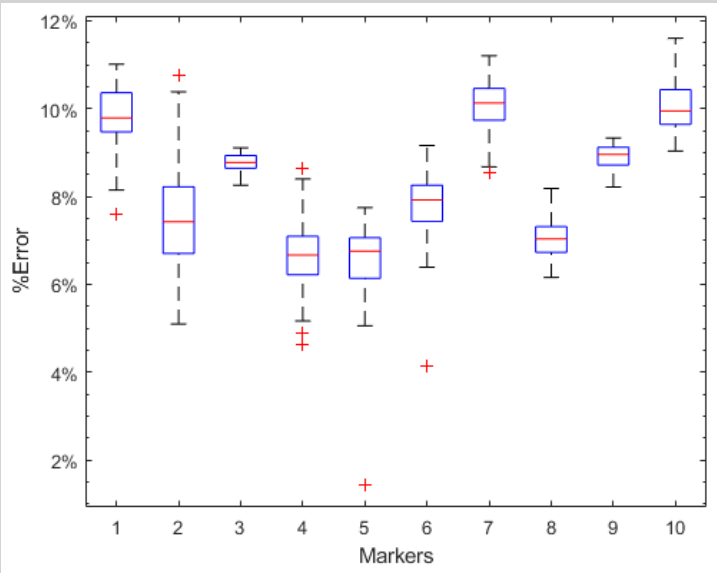
Validation Data
- Depth Camera

Accuracy in distance measurements

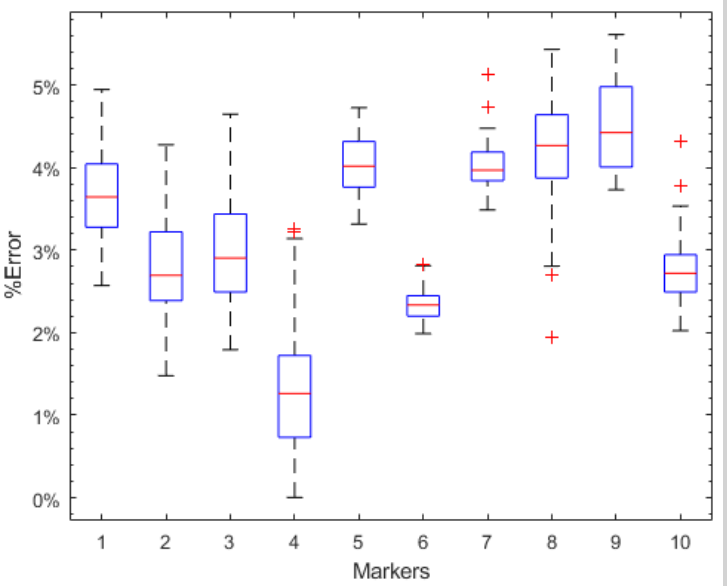
1. High brightness – High contrast



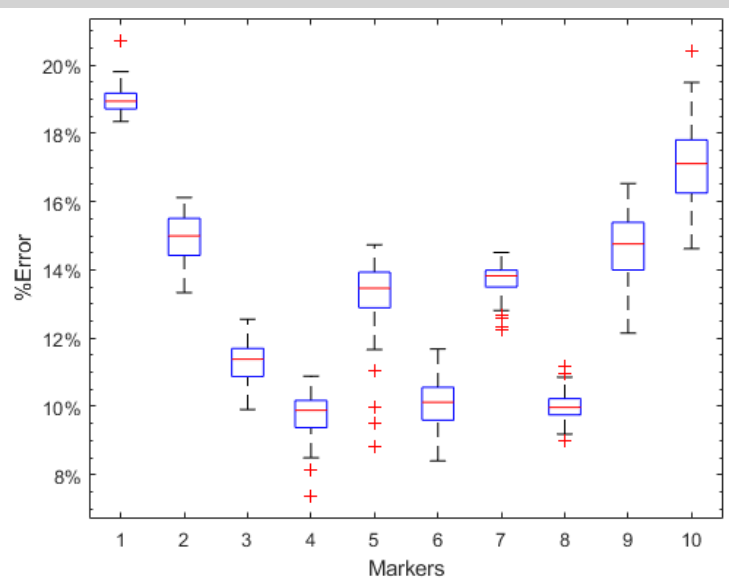
2. High brightness – Low contrast



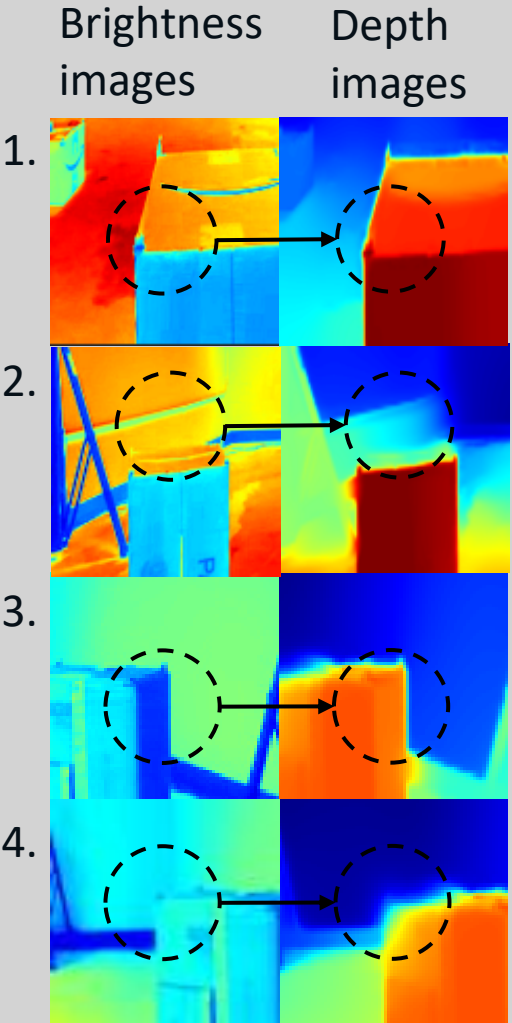
3. Low brightness – High contrast



4. Low brightness – Low contrast



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



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.

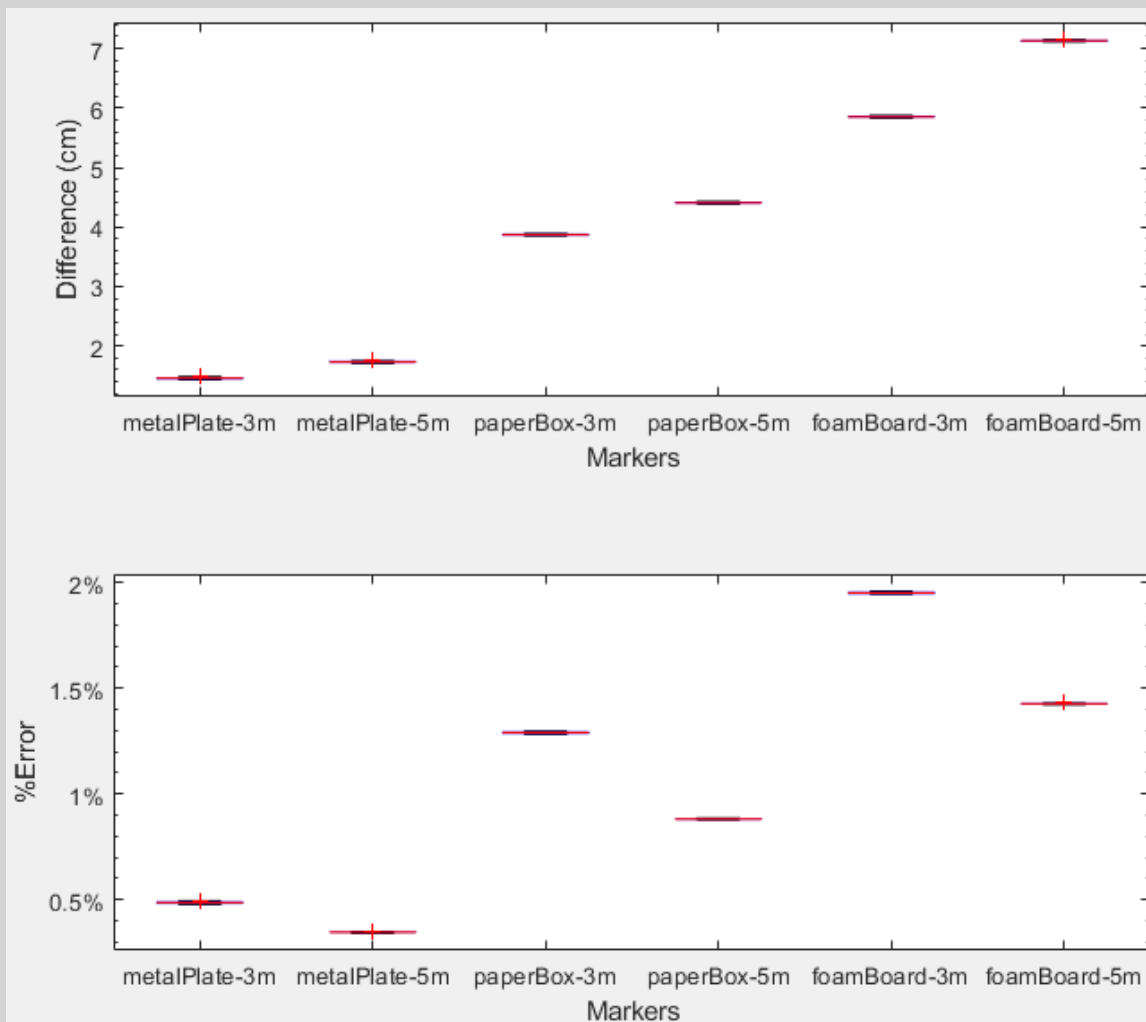


OptiTrack:

A set of fixed optical camera sensors that can provide accurate measurements with positional error $< 0.3\text{mm}$, and rotational error $< 0.05^\circ$

*Thank Prof. Rahaim for his OptiTrack system

Distance measurement comparison



- Antenna array size: 64 x 24
- Range resolution $\cong 3.8\text{cm}$
- Elevation angular resolution $\cong 1.8^\circ$
- Azimuth angular resolution $\cong 4.8^\circ$

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>

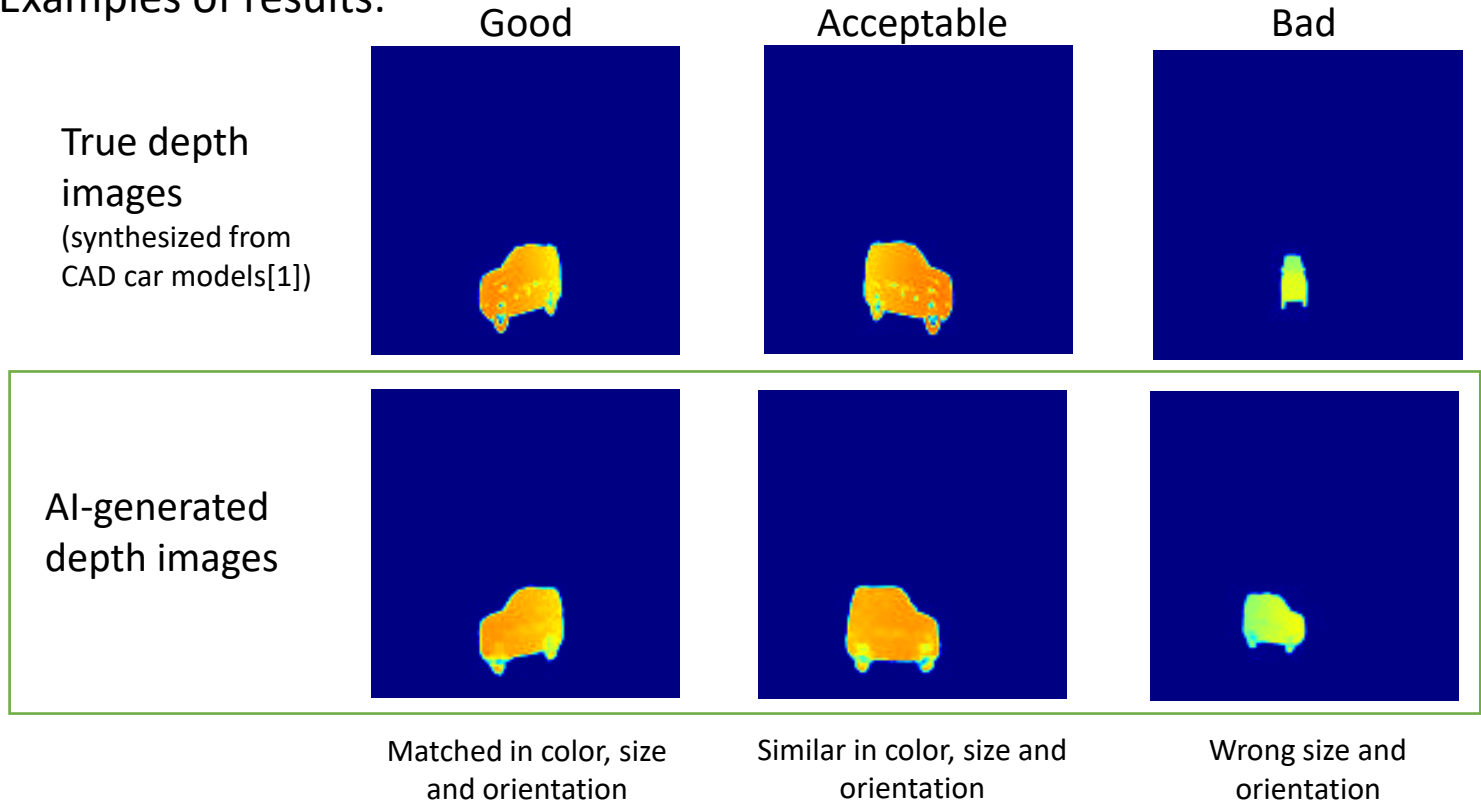


Test 3: Neural Network

- 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:



Train	2475		
Verify	25		
Good	14	56%	80%
Acceptable	6		
Bad	5		

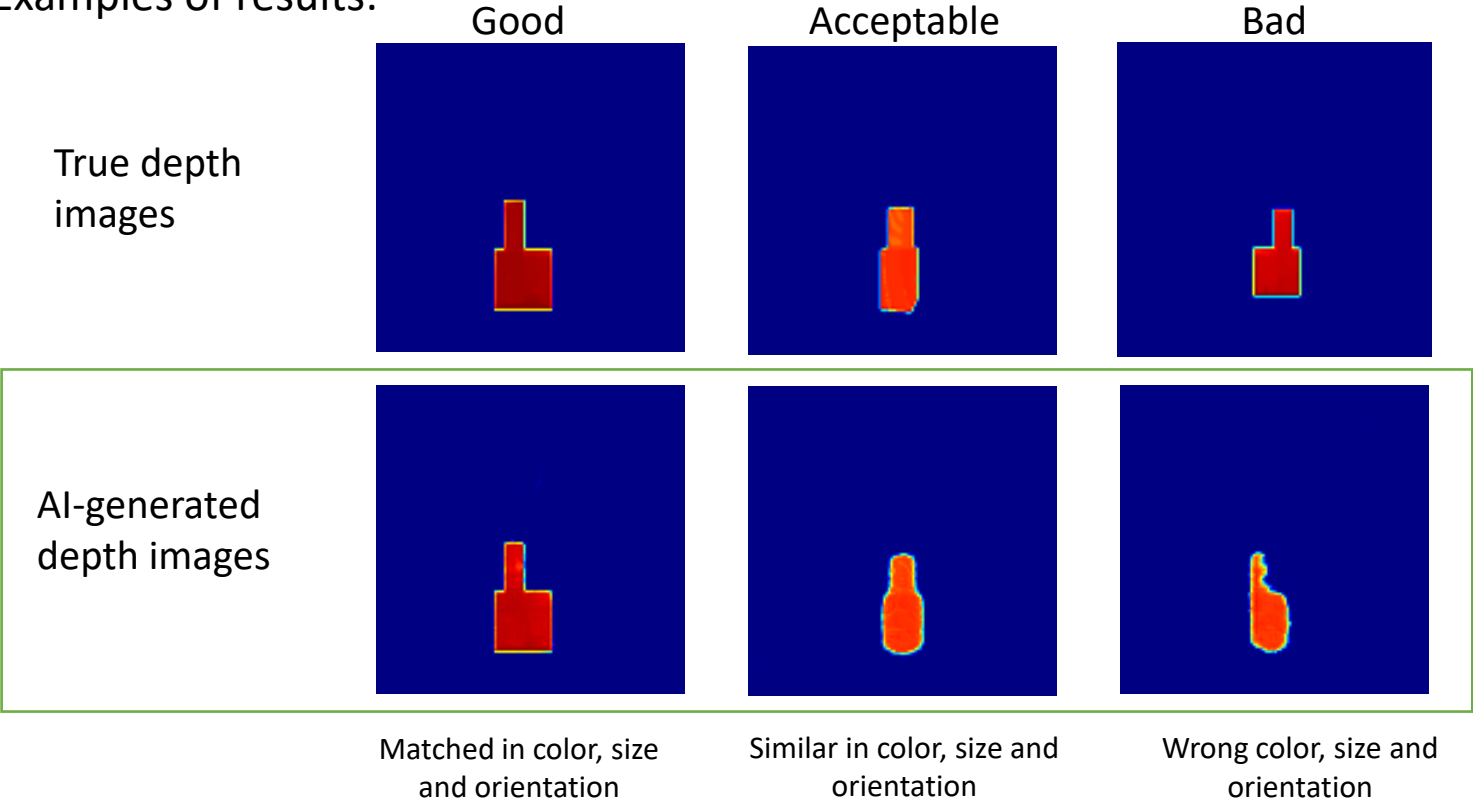
Generator losses	
G_GAN:	0.693
G_L1(*1000):	2.861
G_Lp(*20):	21.452
Discriminator losses	
D_real:	0.440
D_fake:	0.693

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:



Train	2500		
Verify	300		
Good	125	42%	77%
Acceptable	106		
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

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

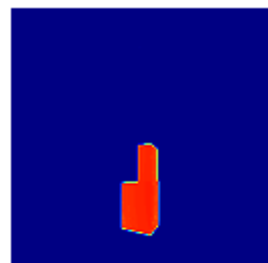
Time (min)	Battery Voltage (V)
0	12.51
5	12.40
10	11.99
15	11.16
20	10.95

100% Throttle

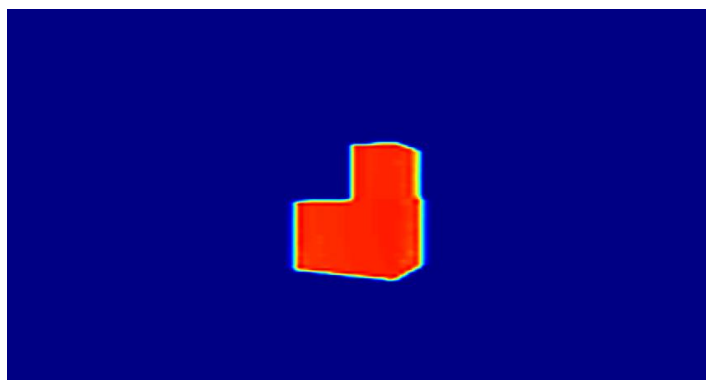
Time (min)	Battery Voltage (V)
0	12.60
5	11.73
10	11.34
15	11.13
20	9.65

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

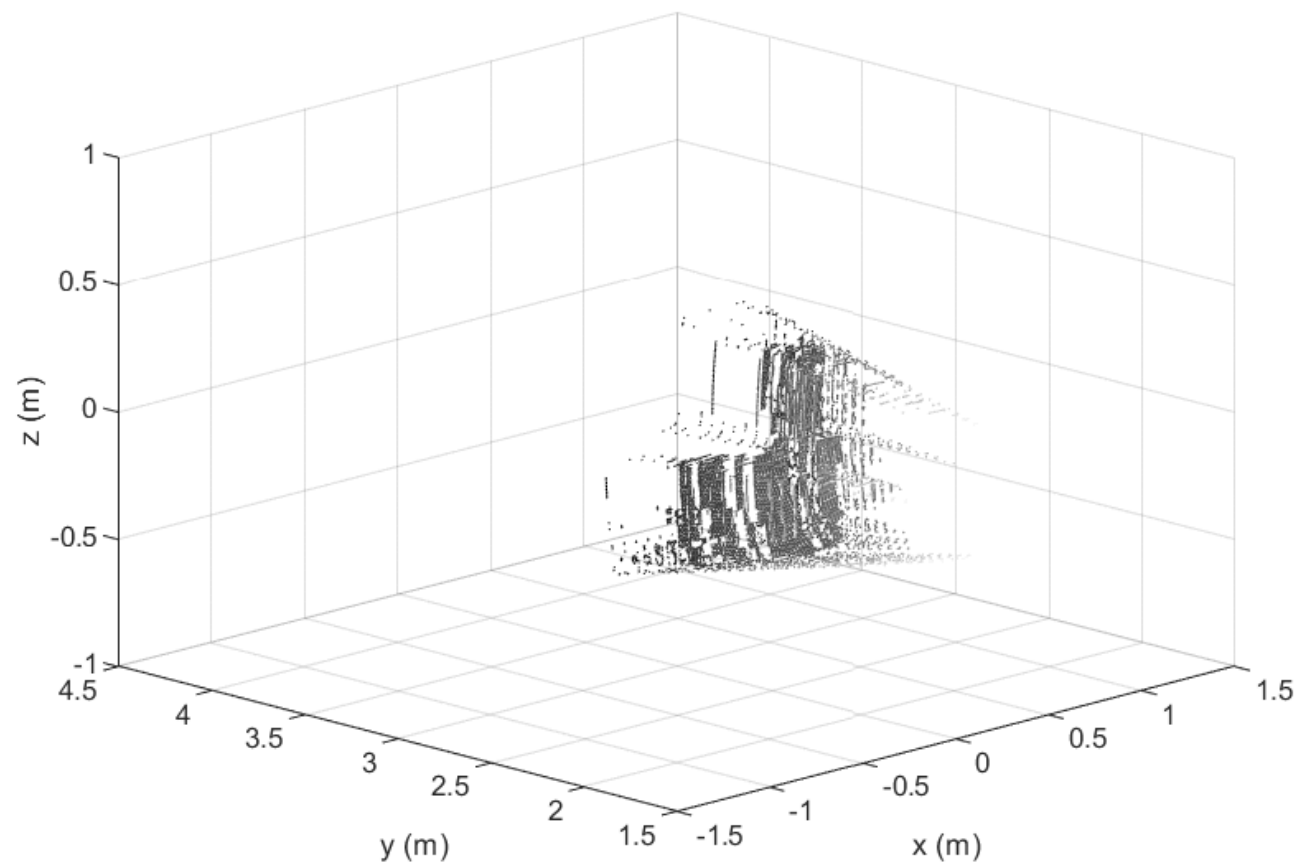
Example Result



128x128
(size for model training)



1280x720
(original size)



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

- 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)

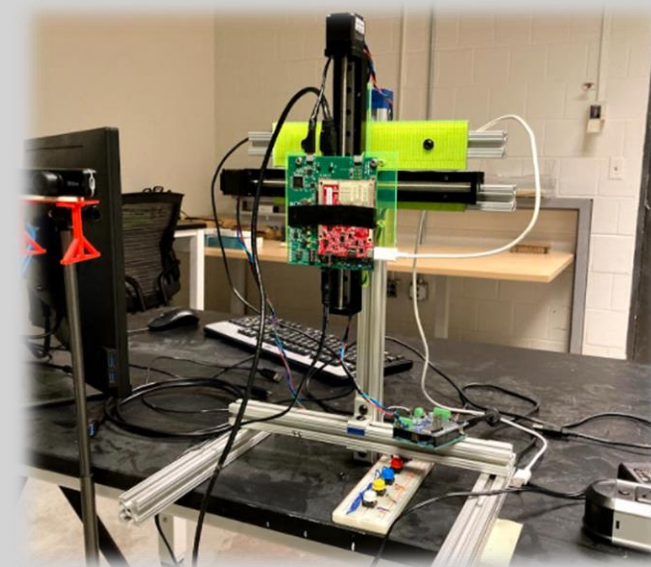


Fig. 1

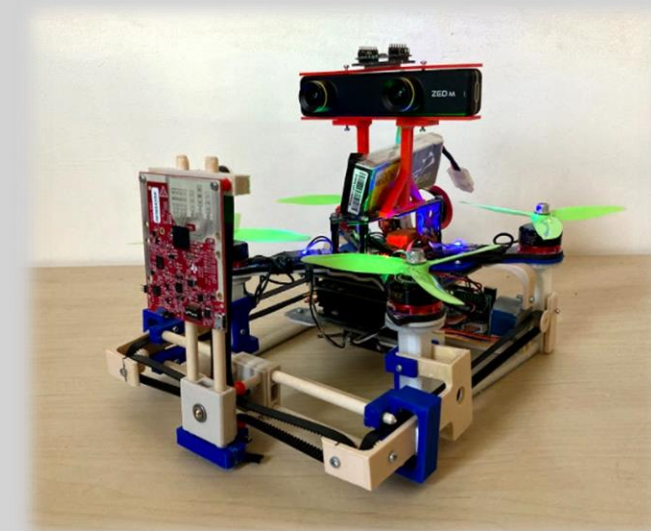


Fig. 2

- 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

- [1] J. Guan, S. Madani, S. Jog, and H Hassanieh. "High Resolution Millimeter Wave Imaging for Self- Driving Cars.". 2020. IEEE CVPR (2020).
- [2] S. Fang and S. Nirjon. "SuperRF: Enhanced 3D RF Representation Using Stationary Low-Cost mmWave Radar." 2020. International Conference on Embedded Wireless Systems and Networks (EWSN), Vol. 2020. NIH Public Access, 120.
- [3] Texas-Instruments, IWR6843ISK, 2021 [Online]. Available: <https://www.ti.com/tool/IWR6843ISK>
- [4] Texas-Instruments, DCA1000EVM, 2021 [Online]. Available: <https://www.ti.com/tool/DCA1000EVM>
- [5] STEREO LABS, ZED mini, 2021 [Online]. Available: <https://www.stereolabs.com/zed-mini/>
- [6] LEYARD, OptiTrack, 2021 [Online]. Available: <https://optitrack.com/>

Thank you

Question?